Determination of Absorbed Dose
Why the Monte Carlo based method is very a useful add-on?

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1. Background: Reference dosimetry

Radiation transport which finally leads to the deposition of absorbed dose to the material in a volume of interest is complex. Therefore, determination of absorbed dose by calculations solely based on the knowledge the physical processes involved is a difficult task.

Nowadays, the most accurate way to approach the problem and determine absorbed dose in water as shown in Fig. 1 is the use of a calibrated ionization chamber in combination with well-established procedures and correction factors described for instance in the International Code of Practice TRS 398 [1]. According to TRS 398, the absorbed dose to water at the reference depth in water for a reference beam of quality and in the absence of the chamber is given very simply by:

$$D_{w,Qo} = M_{Qo} \; N_{D,w,Qo} \qquad (1)$$

where M_{Q_0} is the reading of the dosimeter under the reference conditions used in the standards laboratory and $N_{D.W,Q_0}$ is the calibration factor in terms of absorbed dose to water of the dosimeter obtained from a standards laboratory. In most clinical situations the measurement conditions do not match the reference conditions used in the standards laboratory. This may affect the response of the dosimeter and it is then necessary to differentiate between the reference conditions used in the standards laboratory and the clinical measurement conditions. In that case, one must apply well established correction factors, for instance the beam quality correction factor k_{Q,Q_0}, when a dosimeter is used in a beam of quality Q different from that used in its calibration. For reference conditions, these correction factors are given in the TRS 398 documents. As a result, the relative standard uncertainty in the determination of absorbed dose under reference conditions may result at a level between 1% and 2%.

2. Dosimetry under non-reference conditions

However, it may happen that the clinical measurement conditions deviate from reference conditions as covered by TRS 398 in such a way that the necessary correction factors are not directly available. Important examples, for instance shown in Fig. 2 are the use of solid state detectors such as silicon detectors or diamond dosimeters [12], or a measurement in a phantom material other than water.

3. The MC simulation for dose calculations: What does it conceptually offer?

MC dose calculations may appear cumbersome, quite time consuming and doable only for specialists [2]. However, they can also tell us a series of important insights. Fundamental in dosimetry is the fact that the total absorbed energy in a volume of interest consists of single energy deposits of random nature. In MC simulations, the equivalent of an energy deposit, is a single energy loss along a charged particle track, de_i which is obtained either by a single electron step or by a condensed history step. Since the total energy absorbed (and thus the absorbed dose) consists almost exclusively by such processes, it is equivalent to say that MC dose calculations are essentially based on tracking the fate and the associated energy losses of electrons.

Based on this fact, the radiological quantity CEMA now gets more attention. It is originally defined as the quotient of the mean

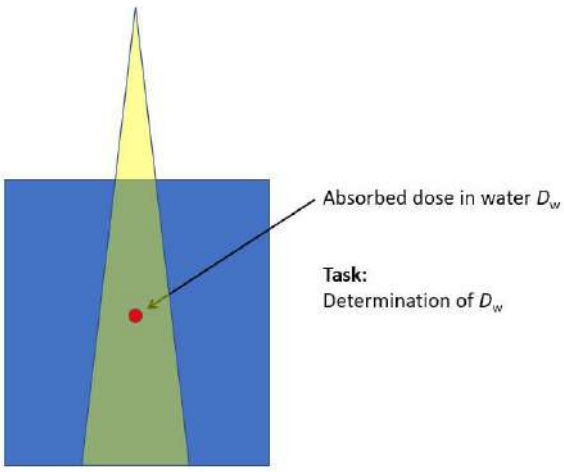

Figure 1: Schematic assembly for the determination of the water absorbed dose within a water phantom.

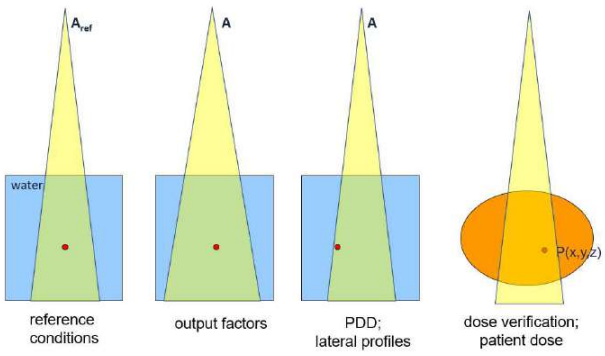

Figure 2: various non-reference measuring conditions

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energy which is lost in electronic interactions in a mass dm of a material by charged particles (mostly electrons), except secondary electrons, incident on dm [14]. The most interesting consequence, however, is that a similar quantity, the restricted CEMA, C_Δ is almost equal to the MC calculated absorbed dose in a volume of interest (VOI) [14]. The restricted CEMA can be expressed by a quite simple expression using MC calculated values of the fluence of electrons differential in energy, Φ_E:

$$D \approx C_\Delta = \sum_{i=1}^{N} \left[\Phi_E \cdot \left(\frac{L_\Delta}{\rho}\right)\right]_i \qquad (2)$$

where i refers to an energy binning of the kinetic energy of the electrons. Most appropriate is a linear binning with 5 keV bin width in case that $\Delta = 10\ keV$ is used. $(\frac{L_\Delta}{\rho})$ is the restricted mass stopping power of the material in the VOI at bin i. For details, in particular for the summation in eq. (2) see Hartmann & Andreo: Fluence calculation methods in Monte Carlo dosimetry simulations [11], and Hartmann et al: Cema-based formalism for the determination of absorbed dose for high energy photon beams [13].

Although the equality between D and C_Δ is an approximation only, it is a very good approximation: for instance at 6 MV photon radiation the difference is less than 0.01%. Subsequently, it is called the CEMA approximation. The volume of interest (VOI) may be of any shape, for instance a cubic voxel, a disc shaped or spherical volume, or the sensitive volume of a dosimeter.

Note: Calculation of C_Δ can be quite easily performed with EXCEL by using:

(a) the values for the restricted mass stopping power, $(\frac{L_\Delta}{\rho})$; they can be found in the literature;

(b) values for fluence differential in energy at bin i, $\Phi_{E,i}$; quite recently they can be obtained by a new version of the MC code 'egs chamber' of the EGSnrc system, see Failing et al: Enhancement of the EGSnrc code 'egs chamber' for fast fluence calculations of charged particles. [8];

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4. Use of the electron fluence: A formal approach for correction factors

A very general application of the spectral electron fluence and the Cema based expression of equation (2) can be formulated for the dose determination under any non-reference condition:

$$D_{w,Q} = M_{Qo}\ N_{D,w,Qo}\ f_{Q,Qo} \qquad (3)$$

where f_{Q,Q_0} is a short term for the ratio $,f_Q/f_{Q_0}$ is beam quality under measuring conditions and Q_0 is beam quality under calibration conditions. f is a general correction factor [4] which can also be obtained using the CEMA approximation and a quite trivial modification (see Appendix) by:

$$f = \frac{\sum_{i=1}^{N}\left[\Phi_E^w \cdot \left(\frac{L_{\Delta,w}}{\rho}\right)\right]_i}{\sum_{i=1}^{N}\left[\Phi_E^w \cdot \left(\frac{L_{\Delta,med}}{\rho}\right)\right]_i} \cdot \frac{\sum_{i=1}^{N}\left[\Phi_E^w \cdot \left(\frac{L_{\Delta,med}}{\rho}\right)\right]_i}{\sum_{i=1}^{N}\left[\bar{\Phi}_E^{VOI} \cdot \left(\frac{L_{\Delta,med}}{\rho}\right)\right]_i} \qquad (4)$$

In this equation $\Phi_{E,i}^W$ is again the fluence differential in energy of the electrons at the point of interest in water, $\Phi_{E,i}^{VOL}$ is the mean fluence differential in energy of the electrons in the VOI, and 'med' denotes the material in the VOI. Calculation of the four sum expressions can again be easily performed using the capacity of EXCEL, the well-known values for the restricted mass stopping $(\frac{L_\Delta}{\rho})$ and MC values for the spectral electron fluence calculated (a) for a small water voxel at the point of measurement and (b) for the VOI.

Note:

- The first factor of f only corrects for the material in the VOI with respect to its stopping power if different from water. This factor is identical with the stopping power ratio according to Spencer and Attix and frequently denoted as $s_{W,med}$.
- The second factor corrects for any occurring deviation of the mean spectral electron fluence in the VOI from the spectral electron fluence in water at the point of measurement. Deviations may be caused by several influence factors such as the VOI material, its shape, or also by the housing if the VOI refers to a detector (wall effect!). A difference may also occur in case of volume averaging, for instance at small beams or at the field edge. This second factor is therefore considered a fluence correction factor, sometimes also called a fluence perturbation correction factor p.

Thus equation (4) can also be written in an abbreviated formulation as:

$$f = s_{w,med}\ p \qquad (5)$$

This derivation of eq. (5) is the most important consequence of the MC method in combination with the CEMA approach as expressed by eq. (2).

It should be mentioned that this equation is already well known based on the classical cavity theory applied to ionization chambers [1,2,4,18,24]. The benefit of the CEMA approach, however, is that a relatively easy and at the same time exact calculation method based on the electron fluence is now available. This characteristic particularly applies for the fluence perturbation . In addition, eq. (5) is generally applicable under any measuring condition, i.e. under reference condition as well as under non-reference conditions.

The summary up to here is:

Without having really performed MC calculations, we can derive a quite fundamental statement on the correction factor which is needed to be applied to equation (1) for the determination of water absorbed dose in a VOI under conditions deviating from calibration conditions. This correction factor is always the product of two factors which separately take into account:

1. The material in the VOI with respect to the stopping power; this is accomplished by the Spencer-Attix stopping power ratio $s_{W,med}$.
2. Any change of the mean spectral fluence of the electrons in the VOI containing the material 'med' with respect to that at the point of measurement; this is accomplished by the fluence correction factor with:

$$p = \frac{\sum_{i=1}^{N}\left[\Phi_E^W \cdot \left(\frac{L_\Delta,\text{med}}{\rho}\right)\right]_i}{\sum_{i=1}^{N}\left[\bar{\Phi}_E^{\text{VOI}} \cdot \left(\frac{L_\Delta,\text{med}}{\rho}\right)\right]_i} \quad (6)$$

The second factor always focuses on the question: what happens with the electron fluence in the VOI? The message of this work is: That question can always be answered by MC calculations of the electron fluence, in other words: drawing the attention from photons to electron (Fig. 3). With the new EGSnrc code 'egs chamber' [8] a tool is available which provide the required data on the electron fluence using robust methods of variance reduction and which therefore can produce useful results also if installed at a modern laptop.

5. A practical application of the fluence correction factor p: Measurement of absorbed dose to water in plastic phantoms

5.1. Introduction

TRS 398 [1] says that in spite of their increasing popularity, the use of plastic phantoms is strongly discouraged for reference measurements (except for low energy X rays), as in general they are responsible for the largest discrepancies in the determination of absorbed dose for most beam types. This is mainly due to uncertainties in the assessment of the density of the plastic material and to the approximate nature of the procedures for scaling depths and absorbed dose from plastic to water. Nevertheless, when accurate chamber positioning in water is not possible, or when no waterproof chamber is available, their use is permitted.

If a plastic phantom is used, two types of corrections or scaling methods are generally required:

1. Scaling of depth into the water-equivalent depth.
2. Scaling of electron fluence.

5.2. Problems

The methods for depth scaling are well established in theory and practice. In case of high-energy photon beams the depth-scaling factor can be obtained by the ratio of the linear attenuation coefficient between the phantom material and water, and, as an approximation, also by the ratio of the corresponding mass density. However, even if the chamber is now positioned at the water-equivalent depth in the plastic phantom, the fluence of the secondary electrons in the chamber may differ from that when placed in water. In this case it must be corrected by a fluence correction factor .

The method for this additional correction is less well established. TRS 398 does not offer any data for high-energy photon beams, which may lead to the wrong assumption that in this case a fluence scaling factor for the determination of water absorbed dose in plastic phantoms is not relevant and therefore, it can be neglected. However, the following, easy-to-perform experiment (Fig. 4) demonstrates that this is not true.

Experiment:

Place an ionization chamber (for instance the Markus-chamber without the water proof shielding) close to the surface of a phantom. Add two further slabs with different materials and associated different mass densities in a certain order and in a

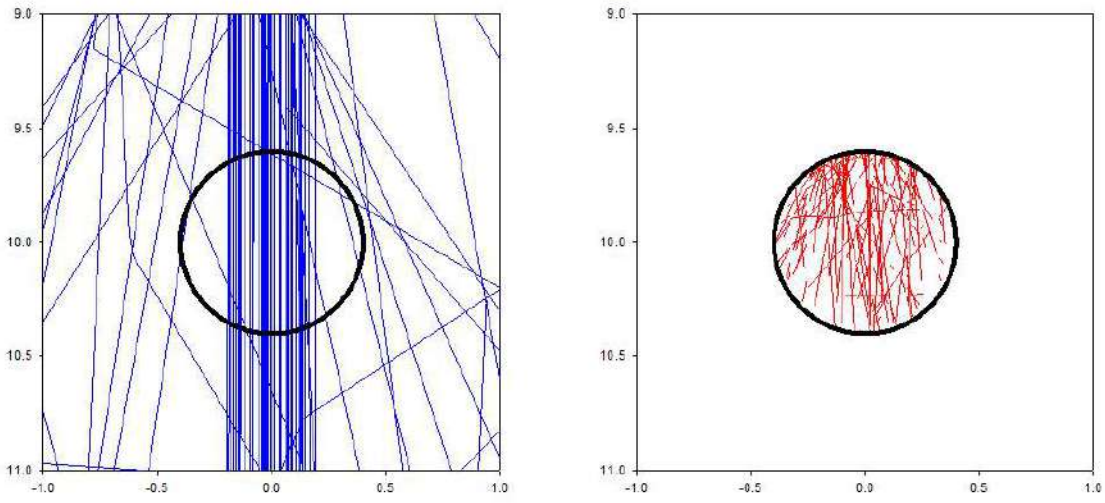

Figure 3: Drawing the attention from photon tracks (left in blue) to electron tracks (right in red), same irradiation condition of a spherical volume of interest with a small photon beam

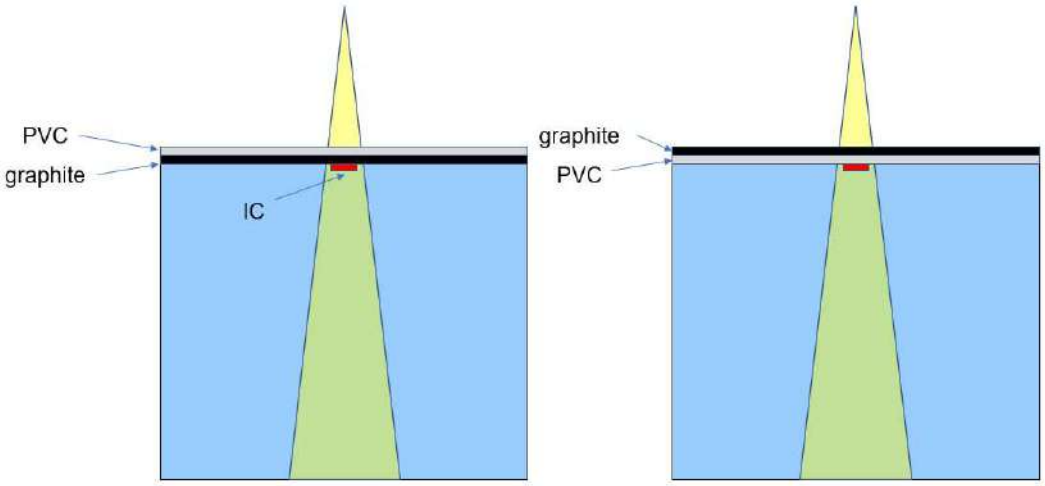

Figure 4: Measuring assembly to demonstrate the influence of non-water materials. left: order of slabs is PVC – graphite; right: reverse order

reversed order on top of the phantom (Fig. 4). Slabs with 5 mm thickness, materials such as made of graphite and polyvinyl chloride (PVC), and 6 MV photon beam are appropriate. Observe the reading of the ionization chamber in the photon beam before and after changing the order of the two slabs.

Finding:
Although the attenuation of the photon beam and thus the water-equivalent depth of the chamber remains almost independent from the order of the two slabs, the chamber reading may differ by up to 8%! This is mainly due to the different characteristics of graphite and PVC with respect to the scattering of the secondary electrons [15].

5.3. A cema based formulation for a fluence correction factor

A cema based expression for the correction factor k_{pl} for an ionization chamber can be derived by the requirement:

$$D_w^w(z_w) = \quad k_{pl} \cdot D_w^{pl}(z_{pl}) \qquad (7)$$

where $D_W^W(Z_W)$ is the water absorbed dose at the point of measurement in water at depth Z_W, and $D_W^{pl}(Z_{pl})$ is the water absorbed dose in the chamber placed in the plastic phantom at the depth Z_{pl} which is the water-equivalent depth of Z_w. Using the CEMA approach it follows:

$$k_{pl} = \frac{D_w^w(z_w)}{D_w^{pl}(z_{pl})} = \frac{s_{w,a}(z_w) \cdot p_w(z_w)}{s_{w,a}(z_{pl}) \cdot p_{pl}(z_{pl})} = \frac{\sum_{i=1}^{N}\left[\Phi_E^W(z_w) \cdot \left(\frac{L_\Delta,\mathrm{med}}{\rho}\right)\right]_i}{\sum_{i=1}^{N}\left[\bar{\Phi}_E^{VOI}(z_{pl}) \cdot \left(\frac{L_\Delta,\mathrm{med}}{\rho}\right)\right]_i} \qquad (8)$$

where $\Phi_E^W(Z_W)$ is the spectral fluence in water at the point of measurement, and $\bar{\Phi}_E^{VOI}(Z_{pl})$ is the mean spectral fluence in the chamber placed in the plastic phantom at depth Z_{pl}. It is additionally assumed that $S_{W,a}Z_W \approx S_{W,a}Z_{pl}$. Expression (8) well reflects the underlying reason for the modified reading in plastic phantoms: a changed electron fluence in the chamber compared to water and specifically a change induced by the surrounding plastic phantom. Although it may be too time consuming to evaluate k_{pl} in a systematic manner, its assessment on a random basis may offer a sufficiently good estimate of the influence of a plastic material on the determination of absorbed dose in plastic phantoms.

6. A further practical application of the fluence correction factor p: the material dependent response of dosimeters

6.1. Introduction

Investigations on the material dependent behavior of the response of dosimeters were addressed in a series of papers on photon beam. Beyond the interest in a characterization of possibly useful properties of solid state detectors in dosimetry, a specific motivation also was to explain the substantial reduction of response in small beam dosimetry with ionization chambers, a reduction which is not observed to this extent with solid state detectors [5,6,7,30]. Frequently this effect was assigned to the deviation of the mass density of the sensitive detector material relative to that of water (see e.g. Scott et al [23,24,25], Bouchard et al [5], Fenwick et al. [9,10], and Underwood et al [28,29]). This explanation is sometimes also referred to as caused by the 'density effect'. Accordingly, a specific 'density perturbation factor' was supposed to correct for this effect in dosimetry.

On the other hand, the paper of Andreo and Benmakhlouf [3] very clearly have shown that the response of materials used in solid-state detectors for 6 MV small photon field dosimetry can be better described in terms of the stopping power ratio detector-to-water. Thus the adequacy of a 'density perturbation factor' or of

an interpretations of detector response in terms of the mass density alone was questioned.

6.2. Dose response

The exact definition of the dose response (or short: response) R is the ratio between detector signal and absorbed dose to water at the position of measurement in a water phantom without detector. Frequently it is also expressed as the ratio between the mean absorbed dose in the sensitive volume of the detector (='det') with the material 'med', $\bar{D}^{det}_{med}$, and the absorbed dose at the point of measurement, D_W, thereby putting aside the intrinsic detector dose response [5]:

$$R = \frac{\bar{D}^{\mathrm{det}}_{\mathrm{med}}}{D_{\mathrm{w}}} \qquad (9)$$

This expression has the advantage of being quantifiable for any detector material regardless whether a detector signal can be generated with a material of interest or not. Furthermore, $\bar{D}^{det}_{med}$ and D_W can be well obtained by MC calculations where D_W refers to a small water volume at the position of measurement [26].

6.3. A CEMA based expression for the detector response

The formulation (9) for detector response can be converted into an equivalent, CEMA based expression.

$$R = \frac{\bar{C}^{\mathrm{det}}_{\Delta,\mathrm{med}}}{C_{\Delta,\mathrm{w}}} \qquad (10)$$

where $\bar{C}^{det}_{\Delta,med}$ is the mean restricted Cema with reference to the material 'med' in the detector and $C_{\Delta,W}$ is the restricted Cema in water at the point of measurement. The Cema based expression now enables a factorization into three sub-factors similar as already applied for the correction factor f in eq. (4). One then obtains:

$$R = \frac{\Sigma_{i=1}^{N}\left[\Phi_E^W \cdot \left(\frac{L_{\Delta,\mathrm{med}}}{\rho}\right)\right]_i}{\Sigma_{i=1}^{N}\left[\Phi_E^W \cdot \left(\frac{L_{\Delta,\mathrm{w}}}{\rho}\right)\right]_i} \cdot \frac{\Sigma_{i=1}^{N}\left[\bar{\Phi}_E^{\mathrm{det}} \cdot \left(\frac{L_{\Delta,\mathrm{med}}}{\rho}\right)\right]_i}{\Sigma_{i=1}^{N}\left[\bar{\Phi}_E^W \cdot \left(\frac{L_{\Delta,\mathrm{med}}}{\rho}\right)\right]_i} \cdot \frac{\Sigma_{i=1}^{N}\left[\bar{\Phi}_E^W \cdot \left(\frac{L_{\Delta,\mathrm{med}}}{\rho}\right)\right]_i}{\Sigma_{i=1}^{N}\left[\Phi_E^W \cdot \left(\frac{L_{\Delta,\mathrm{med}}}{\rho}\right)\right]_i} \qquad (11)$$

Note:

- The first and material dependent factor of the response R only depends on the deviation of the mass stopping power of the detector material 'med' from that of water. It is therefore denoted as R_{stp}.
- The second factor only depends on the deviation of the mean spectral electron fluence in the detector from that in a detector with same shape but filled with water. Deviations of the fluence may be caused by influence factors such as the material or shape. It is therefore denoted as R_{fl}.
- The third factor is due to the averaging effect. It depends on the deviation of the mean spectral electron fluence in the detector filled with water from that in water at the point of measurement. Such deviations occur at small beams or at the field edge. This factor is therefore denoted as R_{vol}.

In summary, the total detector response can be expressed by the following product of three response factors where each of them separately takes into different influence factors:

$$R = R_{stp} \cdot R_{fl} \cdot R_{vol} \qquad (12)$$

Table 1: Detector materials, mass density, and atomic number

Material	Mass density ρ (g cm^{-1})	$\bar{Z}$
Lithium	0.534	3.0
Water	0.998	6.6
Air	1.205 10^{-3}	7.6
Silicon	2.33	14

6.4. Some material examples

The following examples for the material dependent response refer to a simplified detector model, i.e. a wall-less detector consisting of a cylindrical cavity only. The cylinders have a thickness of 1 mm, a diameter of 6 mm, and are filled with the material of interest, specifically with lithium, water, air, and silicon (Tab. 1).

The point of measurement was 1.5 cm for a 6 MV beam in a cubic water phantom with a side length of 30 cm. A point source was used with SSD=95 cm, two circularly shaped beams were applied: a diameter of 2 cm (denoted as large beam) and a diameter of 1 mm (denoted as small beam). Results are given in Tab. 2 for the large beam and in Tab. 3 for the small beam.

These results clearly show:

- The detector response indeed differs with the detector material, however, not in a density dependent manner

Table 2: Detector materials and response factors under the large beam condition

Material	Response R	R_{stp}	R_{fl}	R_{vol}
Lithium	0.815	0.850	0.940	1.019
Water	1.019	1.000	1.000	1.019
Air	0.817	0.806	0.994	1.019
Silicon	0.923	0.786	1.153	1.019

Table 3: Detector materials and response factors under the small beam condition

Material	Response R	R_{stp}	R_{fl}	R_{vol}
Lithium	0.0524	0.851	0.842	0.073
Water	0.0731	1.000	1.000	0.073
Air	0.0438	0.806	0.744	0.073
Silicon	0.0732	0.785	1.274	0.073

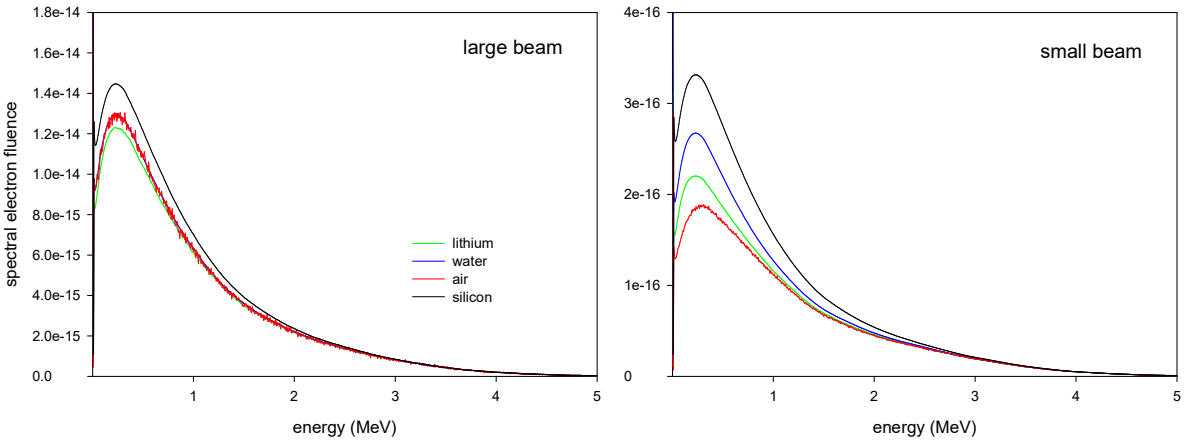

Figure 5: The material dependent spectral electron fluence found for the examples of this subsection.

- The most important influence is the variation of the stopping power ratio which contributes with more than 20%. This influence is equal at both field sizes.
- The change of the electron fluence dependent on the material is found; thus this effect also contributes to the variation of the response (Fig. 5, left). Fluence changes are more pronounced in the small beam (Fig. 5, right).
- A considerable reduction of the response occurs at the small beam size (see also [5,6]. This is clearly due to the volume averaging effect [16,19,20,21]. This effect does not depend on the material.

In summary it can be stated that the material dependent variation of the response is caused by different influence factors, mainly by the stopping power ratio, but also by fluence changes. However, a variation due the mass density is not directly observable, with one exception: under the small beam condition the fluence dependent factor is considerably reduced at the very low density of air. This effect, also referred to as density effect, is well known, but still needs an explanation. A general density correction factor, however, is obviously not required.

7. Summary

It was shown that the MC method yielding data on the electron fluence and thus on CEMA offers a useful tool for the assessment of correction factors required for the determination of water absorbed dose under various measuring conditions. In order to apply this method, the availability of data of the electron fluence differential in energy is an is absolute prerequisite. This can be achieved by a new version of the MC code 'egs chamber' of the EGSnrc system (Failing et al: Enhancement of the EGSnrc code 'egs chamber' for fast fluence calculations of charged particles).

Appendix: The CEMA based derivation of the equation: $f = S_{W,med}p$

The conversion of the absorbed dose between two media, in particular between the dose in a homogeneous medium, for instance water, and that measured in a detector plays a central role in the classical cavity theory [4]. This conversion is usually denoted by a factor f and defined for water as:

$$f_Q = \left(\frac{D_{\mathrm{w}}}{\bar{D}^{\mathrm{VOI}}_{\mathrm{med}}}\right)_Q \qquad \text{(A1)}$$

where the dose is to be determined for a given radiation beam quality Q. D_W is the water absorbed dose at the point of measurement in a water phantom and $\bar{D}^{VOI}_{med}$ is the mean absorbed dose in a volume of interest (VOI) placed at this point and filled with the material 'med'. In a MC calculation it is relatively straightforward to calculate $\bar{D}^{det}_{med}$ as the average energy deposited by all charged particles within the volume of interest divided by its mass. However, calculating the dose at a single point, D_W, requires considering an infinitesimally small volume, an approach that relies on some kind of interpolation process.

In the CEMA approach the values of absorbed dose in eq. (A1) are substituted by the corresponding CEMA values:

$$f = \frac{C_{\Delta,\mathrm{w}}}{\bar{C}^{\mathrm{VOI}}_{\Delta,\mathrm{med}}} = \frac{\sum_{i=1}^{N}\left[\Phi^{w}_{E,w}\cdot\left(\frac{L_{\Delta,\mathrm{w}}}{\rho}\right)\right]_i}{\sum_{i=1}^{N}\left[\bar{\Phi}^{\mathrm{VOI}}_{E,\mathrm{med}}\cdot\left(\frac{L_{\Delta,\mathrm{med}}}{\rho}\right)\right]_i} \qquad \text{(A2)}$$

By a simple extension with the ratio $\frac{C_{\Delta,W,med}}{C_{\Delta,W,med}} = 1$, eq. (A2) can be converted into:

$$f = \frac{C_{\Delta,\mathrm{w,w}}}{\bar{C}^{\mathrm{VOI}}_{\Delta,\mathrm{med,med}}} \cdot \frac{C_{\Delta,\mathrm{w,med}}}{C_{\Delta,\mathrm{w,med}}} = \frac{C_{\Delta,\mathrm{w,w}}}{C_{\Delta,\mathrm{w,med}}} \cdot \frac{\bar{C}^{\mathrm{VOI}}_{\Delta,\mathrm{med,med}}}{C_{\Delta,\mathrm{w,med}}} \qquad \text{(A3)}$$

or using the sum formulation

$$f = \frac{\sum_{i=1}^{N}\left[\Phi^{W}_{E,w} \cdot \left(\frac{L_{\Delta,\mathrm{w}}}{\rho}\right)\right]_i}{\sum_{i=1}^{N}\left[\Phi^{W}_{E,w} \cdot \left(\frac{L_{\Delta,\mathrm{med}}}{\rho}\right)\right]_i} \cdot \frac{\sum_{i=1}^{N}\left[\Phi^{W}_{E,w} \cdot \left(\frac{L_{\Delta,\mathrm{med}}}{\rho}\right)\right]_i}{\sum_{i=1}^{N}\left[\bar{\Phi}^{\mathrm{VOI}}_{E,\mathrm{med}} \cdot \left(\frac{L_{\Delta,\mathrm{med}}}{\rho}\right)\right]_i} \qquad \text{(A4)}$$

Here the first ratio is the MC and fluence based expression of the Spencer-Attix stopping power ratio, $s_{W,med}$ and the second ratio is the MC and fluence based expression for the fluence perturbation factor, p :

$$f = s_{w,med}\, p \qquad \text{(A5)}$$

References

1. Andreo P, Burns DT, Hohlfeld K, Huq MS, Kanai T, Laitano F, Smyth VG, Vynckier S. Absorbed Dose Determination in External Beam Radiotherapy: An International Code of Practice for Dosimetry Based on Standards of Absorbed Dose to Water, IAEA Technical Reports Series no. 398. Vienna: International Atomic Energy Agency; 2000
2. Andreo P. Monte Carlo techniques in medical radiation physics. Phys. Med. Biol. 36, 861–920 (1991)
3. Andreo P and Benmakhlouf H. Role of the density, density effect and mean excitation energy in solid-state detectors for small photon fields. Phys. Med. Biol. 62 1518–32 2017
4. Andreo P, Burns DT, Nahum AE, Seuntjens J, Attix FH. Fundamentals of Ionizing Radiation Dosimetry. Weinheim: Wiley-VCH; 2017.
5. Bouchard H, Seuntjens J, Duane S, Kamio Y, Palmans H. Detector dose response in megavoltage small photon beams. I. Theoretical concepts. Med Phys. 42, 6033–6047, 2015.
6. Crop F, Reynaert N, Pittomvils G, Paelinck L, De Wagter C, Vakaet L and Thierens H. The influence of small field sizes, penumbra, spot size and measurement depth on perturbation factors for micro-ionization chambers. Phys. Med. Biol. 54, 2951–2969, 2009
7. Das IJ, G. X. Ding, and A. Ahnesjo. Small fields: Nonequilibrium radiation dosimetry. Med Phy 35(1), 206–215, 2008
8. Failing T, Hartmann GH, Hensley FW, Keil B, Zink K: Enhancement of the EGSnrc code egs_chamber for fast fluence calculations of charged particles. Z. Med. Phys. 32, 417–427, 2022
9. Fenwick JD, Georgios Georgiou2,3 , Carl G Rowbottom2,3 , Tracy SA Underwood4 , SudhirKumar5 and Alan E Nahum. Origins of the changing detector response in small megavoltage photon radiation fields Phys Med Biol 2018 Jun 8;63(12):125003
10. Fenwick JD, Kumar S., Scott A.J., Nahum, A.E., Using cavity theory to describe the dependence on detector density of dosimeter response in non-equilibrium small fields, Phys. Med. Biol. 58 (2013) 2901–2923
11. Hartmann GH and Andreo P. Fluence calculation methods in Monte Carlo dosimetry simulations. Z. Med. Phys. 29, 239–48, 2019
12. Hartmann GH and Zink K. A Monte Carlo study on thePTW60 019 microDiamond detector. Med. Phys. 46, 5159–72, 2019
13. Hartmann GH, Andreo P, Kapsch R-P, Zink K. Cema-based formalism for the determination of absorbed dose for high energy photon beams. Med. Phys. 48:7461–7475, 2021
14. ICRU. Fundamental Quantities and Units for Ionizing Radiation (Revised), ICRU Report 85a. Bethesda: International Commission on Radiation Units and Measurements; 2011.
15. Li XA, D W Rogers. Electron mass scattering powers: Monte Carlo and analytical calculations. Med Phys . 1995 May;22(5):531-41. doi: 10.1118/1.597582
16. Low DA, Moran JM, Dempsey JF, Dong L, Oldham M. Dosimetry tools and techniques for IMRT. Med Phys. 2011;38:1313–38.
17. Low DA, Parikh P, Dempsey JF, Wahab S, Huq S. Ionization chamber volume averaging effects in dynamic intensity modulated radiation therapy beams. Med Phys. 2003;30:1706–11
18. Nahum AE. Water/air mass stopping power ratios for megavoltage photon and electron beams. Phys Med Biol 1978; 23: 24-38
19. Nahum EA. Cavity theory, stopping power ratios, correction factors. In: Clinical Dosimetry Measurements in Radiotherapy, AAPM summer school (Medical Physics Publishing), 91–136 (2009)
20. Palmans H, Andreo P, Huq MS, Seuntjens J, Christaki K. Dosimetry of Small Static Fields used in External Beam Radiotherapy: An IAEA–AAPM International Code of Practice for Reference and Relative Dose Determination. IAEA Technical Report Series No. 483. Vienna: International Atomic Energy Agency; 2017
21. Pantelis E, Antypas C, Petrokokkinos L, Karaiskos P, Papagiannis P, Kozicki M, et al. Dosimetric characterization of CyberKnife radiosurgical photon beams using polymer gels. Med Phys. 2008;35:2312–20
22. Pappas E, Maris TG, Papadakis A, Zacharopoulou F, Damilakis J, Papanikolaou N, et al. Experimental determination of the effect of detector size on profile measurements in narrow photon beams. Med Phys. 33, 3700–10, 2006
23. Scott A J, Kumar S, Nahum A E and Fenwick J D 2012 Characterizing the influence of detector density on dosimeter response in non-equilibrium small photon fields Phys. Med. Biol. 57 4461–76
24. Scott A J, Nahum A E and Fenwick J D 2008 Using a Monte Carlo model to predict dosimetric properties of small radiotherapy photon fields Med. Phys. 35 4671–84
25. Scott A J, Nahum A E and Fenwick J D 2009 Monte Carlo modelling of small photon fields: quantifying the impact of focal spot size on source occlusion and output factors, and exploring miniphantom design for small-field measurements Med. Phys. 36 3132–44
26. Sempau J, Andreo P, Aldana J, Mazurier J, Salvat F. Electron beam quality correction factors for plane-parallel ionization chambers: Monte Carlo calculations using the PENELOPE system. Phys Med Biol 49 (18), 4427-44, 2004
27. Spencer LV and Attix FH. A theory of cavity ionization. Radiat. Res. 3(3), 239–254 (1955).
28. Underwood T S, Winter H C, Hill M A and Fenwick J D 2013a Detector density and small field dosimetry: integral versus point dose measurement schemes Med. Phys. 40 082102
29. Underwood T S, Winter H C, Hill M A and Fenwick J D 2013b Mass-density compensation can improve the performance of a range of different detectors under non-equilibrium conditions Phys. Med. Biol. 58 8295–310
30. Würfel JU. Dose measurements in small fields. Med Phys Int J. 2013;1:81–90