Reply to ‘Comment on “Origins of the changing detector

response in small megavoltage photon radiation fields”’

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**Abstract**

Andreo and Benmakhlouf (A-B 2017) have disputed a finding of Scott *et al* (2012) that the variation with field-size of the response of small ion chambers and solid-state dosimeters in small megavoltage photon radiation fields can largely be attributed to density. Further evidence for this finding was provided by Fenwick *et al* (2018), but A-B (2018) have now challenged the methodology used in that study. Specifically, A-B suggest that mass stopping-powers of fictitious materials used in Monte Carlo radiation transport calculations should be adjusted with material density according to the polarisation effect, as if the materials were real and created by compressing other real materials.

In this reply, we observe that fictitious materials are not real, and therefore their densities, mass stopping-powers and microscopic radiation interaction cross-sections can be freely and independently chosen to provide the clearest answers to the questions being studied. And we note that the key role played by density in small field detector response was further confirmed by our group back in 2013, using fictitious materials in which mass stopping-powers were varied with density, as preferred by A-B, as well as being held fixed, with very similar results being obtained in both circumstances (Underwood *et al* 2013a).

Key words:  small fields, detector response, density effect, stopping-power, Monte Carlo

1. **Introduction**

Andreo and Benmakhlouf (A-B 2017) have disputed a finding of Scott *et al* (2012) that the variation with field-size of the response of small ion chambers, diodes and diamond dosimeters in small, subequilibium megavoltage photon fields relative to wider fields is attributable largely to detector density rather than mass stopping-power. In a follow-up paper (Fenwick *et al* 2018) we provided further evidence for the finding of Scott *et al*, but aspects of our methodology have been challenged by A-B (2018), and in this note we address the points they raise.

1. **The conclusions of A-B 2017**

A-B (2018) state that the conclusions of their 2017 paper referred *not* to the field-size dependence of detector response, but only to detector response in small fields having a radius of the order of 0.5 cm. The final paragraph of A-B 2017 says (p. 1531)

“*We conclude that the results and discussions presented in this work show that the papers mentioned in the Introduction, assigning differences in detector response in small fields, of the order of 0.5 cm, to the mass and/or electron density, are based on an incomplete interpretation of the physics governing the interaction processes that take place*.”

The papers listed (A-B 2017, p. 1519) include seven from our group (Scott *et al* 2008, Scott *et al* 2009, Scott *et al* 2012, Fenwick *et al* 2013, Underwood *et al* 2013a, Underwood *et al* 2013b, Kumar *et al* 2015), in which we quantified and analysed the variation with field-size of detector response (signal per 1 Gy dose to water) and attributed this variation largely to density. We studied the field-size variation of response because in practice small field measurements are made using detectors that have been cross-calibrated against regular dosimeters in wider fields in which lateral electronic equilibrium is established, and consequently the small field measurements require adjustment by correction factors *k* that account for the field-size variation of response (Alfonso *et al* 2008, IAEA 2017).

In a single small field responses of small ion chambers and solid-state dosimeters differ by orders of magnitude, due to factors such as the volume, density and mass stopping-power of the detector sensitive region. Most of this difference is cancelled out, however, via the cross-calibration in wider fields, leaving only residual variations between detectors due to differences in the field-size dependence of their response. Consequently, we neither focused on differences between the responses of detectors in a single field, nor attributed such differences to a specific factor; rather, we studied the variation of response with field-size, which we attributed largely to density. The conclusion of A-B 2017 addresses and refers to this work, whose focus was the field-size dependence of detector response and its variation with density.

1. **Construction of fictitious materials**

A-B 2018 propose that *“any fictitious material can be created using different combinations of ρ, Z/A and I-value; however, its density-effect corrections and mass electronic stopping powers must correspond to the specific properties assigned to the fictitious material”*.

To illustrate the role played by fictitious materials in our studies, we present an analysis in which small field detectors are represented as simple cavities, and the correction factor *k* is defined as the ratio of dose absorbed by a point of water in a small field to the dose absorbed by the detector cavity in the small field, divided by the same ratio for a large field (Alfonso *et al* 2008, Fenwick *et al* 2018). The *k* factor of a cavity made from silicon, *ksi*, differs from that of a cavity made from water, *kw*. For the purposes of detector design it is useful to determine whether this is due to the difference in density between silicon (2.33 g cm-3) and water (1 g cm-3) or the difference in mass stopping-power. One way to determine this is to use a radiation transport code such as EGSnrc (Kawrakow *et al* 2011) to calculate *k* factors for cavities made of silicon, water and two fictitious materials, one having the 2.33 g cm-3 density of silicon but the mass stopping-powers and microscopic radiation interaction cross-sections of unit density water, and the other the unit density of water but the mass stopping-powers and microscopic cross-sections of 2.33 g cm-3 density silicon (Figure 1).

We have used the EGSnrc Monte Carlo code to calculate *k* values for cylindrical cavities of diameter and length 1 mm, made from silicon, water, the two fictitious materials described above and two alternative fictitious materials described below. Computationally the cavities were aligned with the axis of a 6 MV photon radiation beam, placed 5 cm deep in a water phantom located at 100 cm source-surface-distance, and irradiated using 0.5×0.5 and 4×4 cm2 fields. From the absorbed doses calculated for the cavities, and for a small water voxel in the absence of the cavities, $k\_{Q\_{0.5,4 cm}}^{0.5,4 cm}$ factors were determined which account for differences in detector response between these fields. Results are listed in Table 1 and shown in Figure 1.

Values of $k\_{Q\_{0.5,4 cm}}^{0.5,4 cm}$ calculated for cavities made from the two fictitious materials described above lie close to those of cavities made from real materials of the same density, because *k* varies considerably when density is changed from 1 to 2.33 g cm-3 but little as mass stopping-powers are changed from water to silicon (Table 1, Figure 1 and Scott *et al* 2012, Fenwick *et al* 2018). However, A-B would prefer the *k* factor calculations to have been carried out for alternative fictitious materials, in this case a 1 g cm-3 density material having the mass stopping-power of density 1 rather than 2.33g cm-3 silicon, and a 2.33 g cm-3 density material having the mass stopping-power of density 2.33 rather than 1 g cm-3 water (Figure 1). Mass stopping-power varies with density due to the polarization effect (Heitler 1954, Sternheimer 1984), although the changes can be quite small: working from Figure 1 of A-B’s comments, the restricted mass stopping-powers of silicon of densities 1 and 2.33 g cm-3 differ by around 0.5-1% when averaged over the electron spectrum generated in water by a 6 MV photon beam, compared to a difference of around 20% between unit density water and 2.33 g cm-3 density silicon.

Changes due to the polarization effect were purposefully excluded from our original fictitious materials, causing A-B to view them as erroneous. In fact, $k\_{Q\_{0.5,4 cm}}^{0.5,4 cm}$ values calculated for A-B’s proposed alternative fictitious materials are very similar to those obtained for the original fictitious materials (Table 1), but their interpretation is less straightforward. When the *kw* value of 1.005 obtained for unit density water is compared to the *k* value of 0.962 obtained for the original fictitious material with density 2.33 g cm-3 but the mass stopping-power of unit density water, the 0.043 (± 0.009, two standard deviations) difference in $k\_{Q\_{0.5,4 cm}}^{0.5,4 cm} $is unambiguously due to the change in density alone. Whereas, when the *k*w value for unit density water is compared to the 0.959 *k* value obtained for A-B’s preferred fictitious material having density 2.33 g cm-3 and the mass stopping-power of 2.33 g cm-3 water, it is no longer completely clear whether the 0.046 (± 0.008) difference in $k\_{Q\_{0.5,4 cm}}^{0.5,4 cm}$ values is due to the change in density between the two materials or to the accompanying small change in mass stopping-power (Figure 1).

This difficulty results from the link between mass stopping-power and density generated in real materials by the polarization effect. Factoring this into fictitious materials causes changes in density to be accompanied by changes in mass stopping-power, preventing definitive attribution of the resulting changes in *k* to either density or mass stopping-power. Technically this is a form of procedural confounding (Pelham 2006) which was avoided in our Monte Carlo work by changing density while holding mass stopping-power fixed, leading to A-B’s objection that the mass stopping-powers of the resulting fictitious materials did not authentically reflect those that would result from compressing or expanding real materials.

This concern for the physical authenticity of fictitious substances is a category mistake (Ryle 1949). The fictitious materials are just that: they are made up, not real physical entities; and for the purposes of radiation transport calculations they are entirely defined by their densities, mass stopping-powers and microscopic radiation interaction coefficients, which consequently can be freely and independently selected to provide the clearest answers to the questions being studied. Radiation transport calculations involving such fictitious materials are not erroneous because the densities and mass stopping-powers of these materials cannot be directly and simultaneously realized by compressing a real material, any more than calculations of the acceleration of a particle having half the rest mass of an electron would be erroneous because such a particle does not exist in nature. Rather, the calculations accurately describe radiation transport through the fictitious materials, shedding light on the impact of individual material properties on the transport process more directly than can be achieved using exclusively real materials, in which individual properties such as density and mass stopping power are often associated.

Nonetheless, we have previously computed the variation with density of *k* factors calculated for the sensitive volumes of PinPoint (31006), MicroLion (31018), Diamond (60003) and unshielded diode (60012) detectors (PTW, Freiburg) while changing the mass stopping-powers of fictitious materials with density according to the polarization effect, as preferred by A-B, as well as holding them constant (Underwood *et al* 2013a). The changes in *k* factors calculated in these two circumstances were very similar, showing that *k* was primarily influenced directly by density, rather than indirectly by its effect on mass stopping-power via medium polarization. There is, therefore, no outstanding need for our conclusions to be demonstrated using A-B’s preferred fictitious materials, as we have already done that.

1. **High *Z* detectors, large fields, and the photoelectric effect**

In Figure 2 of A-B 2018 the dose absorbed by an intermediate cavity (Burlin, 1966) is plotted against the atomic number (*Z*) of its medium. The figure illustrates a well-known dosimetry phenomenon: in wide fields (here 10×10 cm2) traversed by many scatter photons with low energies (*E*), doses absorbed by intermediate cavities rise sharply with increasing *Z*, whereas in smaller fields traversed by fewer low energy scatter photons absorbed doses vary less with *Z* (IAEA 2017). This behaviour is due to the photoelectric effect, whose contribution to mass energy absorption coefficients scales roughly proportionally to (*Z*/*E*)3 (Attix 1986a).

The effect limits the accuracy with which dose can be measured using silver halide films (Attix 1986b, LoSasso 2003) and its implications have long shaped small field dosimetry. Diodes with sensitive volumes shielded by tungsten are not recommended for small field dosimetry for just this reason (IAEA 2017). And no manufacturer builds small field dosimeter sensitive volumes from high *Z* materials, although small amounts of higher *Z* materials are sometimes used in other components. For practical small field detectors built largely from lower *Z* materials such as carbon, aluminium and silicon, the effects of photon spectral variations with field-size are much more moderate. And these effects are further controlled by cross-calibrating dosimeters in 3×3 or 4×4 cm2 rather than 10×10 cm2 fields, the former being sufficiently wide to establish lateral electronic equilibrium but narrow enough to limit their photon spectral difference with small fields (‘daisy chaining’, IAEA, 2017). Thus, A-B’s Figure 2 is a useful reminder of the substantial role that atomic number would play in the response of high *Z* detectors in large fields, but has little relevance to current small field dosimetry research.

1. **Semantics**

The phrase

“*… the ‘density perturbation factor’ should in fact be understood in terms of the reduced mass electronic stopping-powers of solid-state detector components relative to water, due primarily to differences in I-values between component materials and water, and secondarily to differences in electronic density*”

was used by Fenwick *et al* (2018) as a paraphrase of

“*… the so-called ‘density perturbation factor’ of Bouchard et al (2009, 2015), Scott et al (2012) and Fenwick et al (2013) should instead be described in terms of the decrease in mass electronic stopping power for solid-state detectors compared to that of water, mainly due to the different I-values and to a lesser extent to the different detector electron density*”

which appeared in A-B (2017), but Fenwick *et al* did not indicate that their paraphrase represented the wording used by A-B. The meaning of the word “*reduced*” has been questioned by A-B (2018), and in the context of the full phrase can be seen to be “decreased” or “lower”.

1. **Conclusions**

The variation with field-size of the response of ion chambers, diodes and diamond detectors in small megavoltage photon radiation fields relative to wider fields is largely attributable to the the densities rather than mass stopping-powers of detector components, a finding we confirmed back in 2013 using the types of fictitious material preferred by A-B, in which mass stopping-powers varied with density according the polarization effect. In our experience, though, it is more useful to hold mass stopping-powers fixed in the fictitious materials when carrying out these studies, thereby eliminating a source of procedural confounding.

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Figure 1. A schematic representation of relationships between the densities and mass stopping-powers (${S}/{ρ}$) of real water and silicon cavity materials (black dots), two fictitious materials (grey dots), and two alternative fictitious materials preferred by A-B (open dots). $k\_{Q\_{0.5,4 cm}}^{0.5,4 cm}$ values calculated for cylindrical cavities made from these materials are also shown.

Alternative fictitious material 1

density 1 g cm-3

(${S}/{ρ}$) that of 1 g cm-3 silicon

$k\_{Q\_{0.5,4 cm}}^{0.5,4 cm}$ factor = 1.010

Fictitious material 2, density 2.33 g cm-3

(${S}/{ρ}$) that of 1 g cm-3 water

$k\_{Q\_{0.5,4 cm}}^{0.5,4 cm}$factor= 0.962

Si, density 2.33 g cm-3

$k\_{Q\_{0.5,4 cm}}^{0.5,4 cm}$factor *= ksi* = 0.967

Alternative fictitious material 2

density 2.33 g cm-3

(${S}/{ρ}$) that of 2.33 g cm-3 water

$k\_{Q\_{0.5,4 cm}}^{0.5,4 cm}$ factor= 0.959

density

Water, density 1 g cm-3

$k\_{Q\_{0.5,4 cm}}^{0.5,4 cm}$factor *= kw* = 1.006

Fictitious material 1, density 1 g cm-3

(${S}/{ρ}$) that of 2.33 g cm-3 silicon

$k\_{Q\_{0.5,4 cm}}^{0.5,4 cm}$factor= 1.007

Mass stopping-power

Table 1. $k\_{Q\_{0.5,4 cm}}^{0.5,4 cm}$ factors calculated for cylindrical cavities of diameter and length 1 mm, filled with water, silicon, fictitious materials 1 and 2, and alternative fictitious materials 1 and 2 (see Figure 1). The $k\_{Q\_{0.5,4 cm}}^{0.5,4 cm}$ values were calculated as ${\left({D\_{w-point}}/{\overbar{D}\_{cav}}\right)\_{Q\_{0.5 cm}}^{0.5 cm}}/{\left({D\_{w-point}}/{\overbar{D}\_{cav}}\right)\_{Q\_{4 cm}}^{4 cm}}$ where $\overbar{D}\_{cav}$ denotes the average dose absorbed by the cavity, *Dw-point* the dose absorbed at a point at the cavity centre when the cavity is filled with water, the super and subscripts indicate field-size and quality, and 0.5 cm denotes a 0.5×0.5 cm2 field.

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| --- | --- |
| Cavity medium | Calculated $k\_{Q\_{0.5,4 cm}}^{0.5,4 cm}$ ± 2 standard deviations |
| Water | 1.006 ± 0.006 |
| Fictitious material 1  | 1.007 ± 0.007 |
| Alternative fictitious material 1 | 1.010 ± 0.007 |
| Silicon | 0.967 ± 0.007 |
| Fictitious material 2 | 0.962 ± 0.007 |
| Alternative fictitious material 2 | 0.959 ± 0.006 |