Calculations for plane-parallel ion chambers in $^{60}$Co beams using the EGSnrc Monte Carlo code

Ernesto Mainegra-Hing, a) Iwan Kawrakow, and D. W. O. Rogers
Ionizing Radiation Standards, National Research Council of Canada, Ottawa K1A OR6, Canada

(Received 31 December 2001; accepted for publication 15 November 2002; published 17 January 2003)

The EGSnrc Monte Carlo simulation system is used to obtain, for 10 plane-parallel ionization chambers in $^{60}$Co beams, the correction factors $K_{\text{comp}}$ and $P_{\text{wall}}$ that account for the nonequivalence of the chamber wall material to the buildup cap and the phantom material, respectively. A more robust calculation method has been used compared to that used in previous works. A minor conceptual error related to the axial nonuniformity correction factor, $K_{\text{an}}$, has been identified and shown to have an effect of about 0.2%. The assumption that $P_{\text{wall}}$ in-phantom is numerically equal to $K_{\text{comp}}$ calculated for a water buildup cap is shown to be accurate to better than 0.06%, thereby justifying the use of $K_{\text{comp}}$ calculations which are much more efficient. The effect on the calculated dose to the air in the cavity of the particle production threshold and transport energies used in the simulations is studied. Uncertainties in the calculated correction factors due to uncertainties in the photon and electron cross-section data are studied. They are 0.14% and 0.24%, respectively (1 standard deviation), for $K_{\text{comp}}$ factors. The uncertainties on $K_{\text{wall}}$ factors are 0.03% from photon cross-section uncertainties and negligible from electron cross-section uncertainties. A comparison with previous EGS4/PRESTA calculations shows that present results are systematically higher by an average of 0.8%, ranging from 0.4% up to 1.4%. The present results are in better agreement with reported experimental values. [DOI: 10.1118/1.1536291]

I. INTRODUCTION

Plane-parallel ionization chambers are recommended for use in electron beams, especially at low energies where cylindrical chambers can require fluence perturbation corrections of up to 5%. In photon beams they are suitable for reference dosimetry measurements if a calibration in terms of absorbed dose to water is available at the user beam quality. They can also be employed in proton and heavy ion dosimetry. The main advantages of these chambers are their good depth resolution and, for well-guarded chambers, the lack of a fluence perturbation effect for low-energy electron beams.

The recommended method for calibrating plane-parallel ionization chambers is the cross-calibration method, i.e., comparison with calibrated cylindrical chambers in an electron beam of high energy. However, such high-energy beams are not available at all radiotherapy centers and are seldom at calibration laboratories. When absorbed-dose calibration factors in a $^{60}$Co beam are used, the $P_{\text{wall}}$ correction factor is required in $k_{b}$ based protocols to account for the difference between the wall material and the water of the phantom.

When using cross-calibration methods or measured values of $P_{\text{wall}}$, the uncertainty associated with the use of cylindrical chambers is transferred to plane-parallel ionization chamber dosimetry. For those experimental techniques which measure $P_{\text{wall}}$ based only on air-kerma calibrations from a single standards laboratory, or absorbed-dose calibrations from a single source, the uncertainty in the measured $P_{\text{wall}}$ values is independent of the primary standards used, but highly dependent on cavity theory and various correction factors. For those techniques which use both air-kerma and absorbed-dose calibration factors, the measured $P_{\text{wall}}$ values are also directly related to the ratio of $N_{P,w}$ over $N_{K}$. Since the average value of $N_{K}$ at standards labs is expected to increase by about 0.8% in the next few years due to changes in the wall attenuation and scatter correction, $K_{\text{wall}}$ and the point of measurement correction, $K_{\text{an}}$, the values of $P_{\text{wall}}$ measured this way will need to be decreased by the same amount. In any event, there are many good reasons for a considerable spread observed in the experimental $P_{\text{wall}}$ values reported by different authors.

Correction factors for the calibration of ionization chambers have often been calculated using Monte Carlo techniques. The fundamental approach on how to calculate these factors using these techniques was presented by Bielajew et al. The wall attenuation and scatter correction factor $K_{\text{wall}}$ ($A_{\text{wall}}$ in the AAPM TG-21 protocol), the chamber response $k_{m}$ (see Sec. II D for definition), the in-phantom correction factor for the nonequivalence of chamber material and phantom material, $P_{\text{wall}}$, and the in-air correction factor for the composite nature of the chamber wall and buildup cap, $K_{\text{comp}}$, were calculated previously for five plane-parallel ionization chambers using the EGS4/PRESTA Monte Carlo simulation system. The calculations generally agreed with measured values within about 1.0% (with one difference of 1.7%). This level of disagreement was still reasonable considering the estimated minimum 1% (1σ) systematic uncertainty in the calculated values and the uncertainties in...
the measured data. In a more recent work\textsuperscript{23} the values were recalculated using the same computer code and input data as used previously but with much better statistical precision. In addition, the Attix and Roos chambers were included and $P_{\text{wall}}$ values applicable in water phantoms were calculated. The new values made agreement with experiment worse than before. At the same time, comparisons with reported\textsuperscript{13,14} $P_{\text{wall}}$ measurements in water were in reasonable agreement given the respective uncertainties.

Recently, an improved version of the EGS Monte Carlo simulation system, called EGSnrc\textsuperscript{24,25} was released. Kawrakow demonstrated that EGSnrc produces step-size-independent and artifact-free results in the calculation of ion chamber response within 0.1% of the theoretical answer.\textsuperscript{26} The goal of the present work is to recalculate the wall correction factors $K_{\text{comp}}$ and $P_{\text{wall}}$ for plane-parallel ionization chambers in a $^{60}\text{Co}$ beam using EGSnrc and validate them against the predictions of Spencer–Attix cavity theory and reported experimental data. At the same time we want to assess the differences from values calculated previously using EGS4/PRESTA and calculate $k_{\text{gr}}, k_{\text{air}}$ and $k_{\text{ecal}}$, key quantities for the calibration of these chambers in air and water. As long as $^{60}\text{Co}$ remains a reference beam quality for the calibration of plane-parallel chambers in electron beams using absorbed-dose based protocols (AAPM TG-51,\textsuperscript{5} IAEA TRS-398\textsuperscript{6}), $P_{\text{wall}}$ correction factors for plane-parallel ionization chambers in water phantoms irradiated by $^{60}\text{Co}$ beams play an important role in electron beam dosimetry for the realistic chamber, then $K_{\text{comp}}$ belongs in the denominator of the equation for $N_{\text{gas}}$\textsuperscript{27} It is for this reason that values of these quantities are needed to apply protocols based on air-kerma calibration factors\textsuperscript{1,3,28} using plane-parallel chambers.

The corresponding equation for the dose to medium is:

$$D_{\text{med}} = D_{\text{air}} \left( \frac{L}{\rho} \right)^{\text{med}}_{\text{wall}} P_{\text{wall}} P_{\text{repl}},$$

(2)

where $P_{\text{wall}}$ corrects for the fact that the ion chamber is not made of the same material as the medium and $P_{\text{repl}}$ accounts for the effects of the cavity rather than medium being present. This equation is the basis of protocols based on air-kerma calibrations\textsuperscript{1,3,28} and those based on absorbed-dose calibrations.\textsuperscript{5,6} In particular $P_{\text{wall}}$ for a plane-parallel chamber in a $^{60}\text{Co}$ beam is part of the $k_{\text{ecal}}$ factor in the AAPM’s TG-51 protocol.\textsuperscript{2}

Since the definitions of these correction factors are somewhat arbitrary (see, e.g., Ref. 29 for more discussion and an example of using different definitions), the following equations are used to define the correction factors as used here:

$$K_{\text{comp}} = D_{\text{air}}^{\text{ecal,pt}} = D_{\text{homo,pt}}^{\text{air}},$$

(3)

$$K_{\text{air}} = D_{\text{homo,}}^{\text{air}},$$

(4)

$$K_{\text{wall}} = D_{\text{homo,unatten}}^{\text{air}},$$

(5)

where the superscripts imply that the $D_{\text{air}}$ is for the conditions specified: real means for realistic chamber materials; homo means for a chamber of just one material (usually the buildup cap material); pt means for a point source; || means for an incident parallel beam; and unatten means that scatter and attenuation in the walls do not exist. These equations tell us, e.g., that $K_{\text{comp}}$ corrects $D_{\text{air}}$ from being for the realistic chamber in a point source beam to being for a homogeneous chamber in the same beam. Note that these definitions imply that $K_{\text{wall}}$ is the attenuation and scatter correction for a homogeneous chamber in a parallel beam. This follows because we want $K_{\text{comp}}$ to include all corrections related to the different components in the wall, and if $K_{\text{wall}}$ were defined for the realistic chamber, then $K_{\text{comp}}$ would not include the correction for differences in attenuation and scatter.

Using these definitions, it is clear that the corrections $K_{\text{comp}}$ and $P_{\text{wall}}$ are conceptually the same.\textsuperscript{20,23} They both correct for the nonhomogeneous nature of the ion chamber compared to its buildup cap or the phantom, and, they both apply in a point source beam. As will be shown below, they also have numerically equal values (for the in-air case with a water buildup cap) because the attenuation and scatter of the primary beam in the phantom have a negligible effect on the value.

II. METHODS

A. Background theory

Since there have been several conceptual errors in the previous papers on this subject and we are introducing a new method to do these calculations, it is essential to outline the basics in some detail. The fundamental equation for air-kerma free-in-air, $K_{\text{air}}$, is given by\textsuperscript{27}

$$K_{\text{air}} = \frac{D_{\text{air}}}{(1 - g_{\text{air}})(L/\rho)} K_{\text{wall}} K_{\text{air}} K_{\text{comp}} = \left( \frac{L}{\rho} \right)^{\text{air}}_{\text{wall}} K_{\text{wall}} K_{\text{air}} K_{\text{comp}} K \text{(Gy)},$$

(1)

where $D_{\text{air}}$ is the dose to the air in the cavity and is proportional to the measured charge, $g_{\text{air}}$ is the fraction of the energy lost in radiative events by electrons slowing in air, $(L/\rho)_{\text{wall}}$ is the Spencer–Attix electron collision mass stopping-power ratio for the wall material to dry air, $(\mu_{\text{em}}/\rho)_{\text{wall}}$ is the ratio of mass energy absorption coefficients averaged over the spectrum for dry air to the wall material, $K_{\text{wall}}$ corrects for the attenuation and scatter in the wall, $K_{\text{air}}$ corrects for the axial nonuniformity due to the point source nature of the beam instead of the photon beam being parallel, $K_{\text{comp}}$ is a correction for the composite, i.e., nonuniform, nature of the wall material (if any) and $K$ includes various other corrections for other nonideal conditions (e.g., corrections for stems, central electrodes of different material from the wall, radial nonuniformity of the beam, any breakdown in Spencer–Attic cavity theory, etc., all taken as unity in this study).

The equation for $N_{\text{gas}}$ in the TG-21 protocol is tightly linked to Eq. (1) and the product of $K_{\text{wall}} K_{\text{air}} K_{\text{comp}}$ belongs in the denominator of the equation for $N_{\text{gas}}$.\textsuperscript{27} It is for this reason that values of these quantities are needed to apply protocols based on air-kerma calibration factors\textsuperscript{1,3,28} using plane-parallel chambers.

The standard method for calculating $K_{\text{comp}}$ has been to calculate the relevant quantities using Monte Carlo tech-
niques and apply Spencer–Attix cavity theory [Eq. (1)] to the irradiation in air of a plane-parallel ionization chamber:

\[
K_{\text{comp}} = \frac{\left( \frac{D_{\text{air}}}{\rho_{\text{med}}} \right)_{\text{wall}} \left( \frac{\mu_{\text{en}}}{\rho_{\text{med}}} \right)_{\text{air}}}{K_{\text{wall}} (1 - g_{\text{air}})}.
\]

(6)

where \( \text{med} \) is the primary material in the chamber or the buildup cap. This equation is very similar to that used previously.\(^{20,23} \) However, Eq. (6) explicitly recognizes the \( K_{\text{air}} \) correction, which was missing before. The previous failure to include \( K_{\text{en}} \) in the equation showed up as a systematic error of about 0.2% which was un-noticed in the past given the 1% systematic uncertainty in the previous calculations.

In addition, the present definition of \( K_{\text{wall}} \) differs from the previously used definition, which amounted to

\[
K_{\text{wall}}^\text{prev} = \frac{D_{\text{real,pt}}^\text{wall}}{D_{\text{air}}^\text{wall}}.
\]

(7)

The issue of the definition of \( K_{\text{wall}} \) implies that the previous definition of \( K_{\text{comp}} \) was incorrect,

\[
K_{\text{comp}}^\text{new} = K_{\text{comp}}^\text{old,pt} \text{med} \frac{D_{\text{real,pt}}^\text{wall}}{K_{\text{wall}}^\text{old}} = K_{\text{comp}}^\text{old} \frac{D_{\text{real,pt}}^\text{wall}}{K_{\text{wall}}^\text{old}}.
\]

(8)

The product \( K_{\text{comp}}^\text{new} K_{\text{wall}}^\text{old} \) remains invariant using the old or new definitions and this product is all that is needed in comparisons to experiment for in-air measurements. However, this difference does affect the values of \( P_{\text{wall}} \) which are used without \( K_{\text{wall}} \).

During this project, we became aware that using Eq. (6) to calculate \( K_{\text{comp}} \) is directly dependent on our ability to calculate \( D_{\text{air}} \) in an absolute sense, and also on the accuracy of Spencer–Attix cavity theory (e.g., if there is a fluence correction factor needed to correct for the difference between the electron fluence in the cavity vs that in the wall). To avoid both of these uncertainties, we decided to calculate \( K_{\text{comp}} \) directly from its defining equation, Eq. (3), viz.:

\[
K_{\text{comp}} = \frac{D_{\text{air}}^\text{homo,pt}}{D_{\text{air}}^\text{real,pt}}.
\]

(9)

This formulation has the disadvantage of requiring two, rather than one, fairly long calculations of the dose to the air, but it has the advantages that it no longer relies on cavity theory nor any correction factors which are not included, and its dependence on our ability to calculate absolutely the dose to air is greatly reduced since it is the calculation of the ratio of similar quantities.

As argued previously,\(^{20,23} \) if one calculates \( K_{\text{comp}} \) for a buildup cap of water, it has the same value as \( P_{\text{wall}} \) in water in a water phantom on the assumption that the attenuation and scattered photons in the phantom have little effect on the correction. To verify this assumption, we have simulated the realistic plane-parallel ionization chamber at 5 cm depth in a cylindrical water phantom (100 cm\(^2 \) frontal surface by 11 cm length) irradiated with a \(^{60}\text{Co} \) beam and then repeated the simulation with all components of the ion chamber changed to water (except the air cavity). From its definition, the value of \( P_{\text{wall}} \) is given by

\[
P_{\text{wall}} = \frac{D_{\text{air}}^\text{homo,pt}}{D_{\text{air}}^\text{real,pt}},
\]

(10)

which is very similar to Eq. (9) except that in this case, the dose to the air is calculated for an ion chamber in-phantom. This calculation is 3 to 8 times slower than the in-air calculation of \( K_{\text{comp}} \), and thus is only used to prove the validity of the \( P_{\text{wall}} = K_{\text{comp}} \) assumption.

C. Calculational details

The dose to the air in the sensitive region of the cavity, \( D_{\text{air}} \), and the correction for attenuation and scatter in the walls, \( K_{\text{wall}} \), were calculated using the NRC EGSnrc user-code CAVRZnrc\(^{30} \) which is based on the EGSp user-code CAVRZ\(^{17} \) but has been extended and modified for use with EGSnrc. In the original CAVRZ, photons were forced to interact in the geometry in order to increase efficiency. In CAVRZnrc, a photon splitting technique has been introduced which is similar to the one reported by Kawrakow and Fippel.\(^{31} \) For typical ion chamber calculations these increases the efficiency by a factor of 5 compared to using photon interaction forcing.

Stopping-power ratios of medium to air were calculated with the NRC user-code SPRRZnrc\(^{30} \) which makes use of restricted stopping powers based on ICRU Report 37.\(^{32} \) The kerma per unit fluence in a given medium or the mass-energy transfer coefficient was calculated by the EGSnrc user-code DOSRZnrc\(^ {30} \) forcing photons to interact in a very thin slab of material and scoring all the energy transferred on the spot. To get the mass-energy absorption coefficient, the fraction of the electron’s energy lost via radiative processes, \( g \), was calculated using the EGSp user-code \( g \), which scores \( g \) as the ratio of the energy radiated by electrons slowing down in an infinite medium to the total energy transferred by photons to electrons. All quantities were obtained using the \(^{60}\text{Co} \) spectrum from Rogers et al.\(^ {34} \) For a more detailed description of the methods mentioned here, the user is referred to previous publications on this subject.\(^ {17,20,21,33} \)

We use stopping-power ratios calculated with a low energy threshold, \( \Delta \), of 10 keV consistent with: the values used in experimental measurements of \( P_{\text{wall}} \); the values used in all the protocols; and the values used in the previous calculations. Coincidentally the 10 keV value is generally considered appropriate for a 2 mm thick cavity (mean chord length, calculated as described in Ref. 29 is 2.6 mm corresponding to \( \Delta = 10.5 \text{ keV} \)) and for a 1 mm cavity (mean chord length is 1.4 mm corresponding to \( \Delta = 7.4 \text{ keV} \)).

The values of \( K_{\text{comp}} \) and \( P_{\text{wall}} \) were estimated by doing calculations with 0.5 g/cm\(^2 \) buildup caps of the same material as the chamber’s predominant material and water, respectively.
1. Selection of AE, ECUT and related cutoffs

Initially, electrons were followed down to 10 keV kinetic energy (i.e., AE=ECUT=0.521 MeV) but a study of the variation in the dose to the air in the cavity showed that the dose to the air diminishes slightly with decreasing cutoff energy. The calculated dose to the air becomes constant by a cutoff of 0.512 MeV and hence ECUT and AE were both set to 0.512 MeV for the calculation of the dose to the air. The variation in the calculated dose as AE and ECUT were decreased from 0.521 MeV to 0.512 MeV was 0.36% or less (see Fig. 1). The chamber with the largest variation (0.36%) is the Attix chamber which is one of only two chambers with a 1 mm thick air cavity. For all the other chambers, mostly with air cavities about 2 mm thick, the variation is 0.16% or less.

D. Additional quantities

Since one of the goals of this work is to benchmark the EGSnrc code against experimental data for ion chambers, and because there are many data for plane-parallel ionization chamber in air with various buildup caps, it is useful to calculate several other widely used quantities. For in-air calibrations, the IAEA TRS-277 Code of Practice uses the product $k_m k_{att}$ which is given by

$$k_m k_{att} = \frac{D_{air}}{K_{air}(1 - 8_{air})} = \frac{\left(\frac{L_{air}}{\rho_{air}}\right)^{\text{med}} \left(\frac{K_{att}}{\rho_{air}}\right)^{\text{med}}}{K_{comp}K_{wall}},$$

where $K_{air}$ is often not included. We have used the first equality to calculate $k_m k_{att}$.

The quantity $k_{ecal}$ is used in AAPM TG-51’s dose equation when using ionization chambers to calibrate electron beams based on absorbed-dose calibration factors. For well-guarded plane-parallel chambers, $k_{ecal}$ is given by the ratio of two stopping-power ratios divided by $P_{wall}$ (Ref. 23) and, for a reference beam quality of $R_{50}=7.5$ cm, is given by

$$k_{ecal} = \frac{0.9037}{P_{wall}},$$

where we have used our calculated value of 1.1334 for the water to air stopping-power ratio in a $^{60}$Co beam (compared to 1.1334 used in the AAPM’s TG-51). For the Markus and Capintec chambers, the above must be multiplied by $P_{fl}$, the fluence correction factor for the chamber in a beam of quality $R_{50}=7.5$ cm. This correction is 0.998 and 0.993 for the Markus and Capintec chambers, respectively. These are the values used in the AAPM’s TG-51, calculated as described in Ref. 35. The IAEA’s TRS-398 does not use $k_{ecal}$ explicitly, but by definition $k_{ecal} = k_Q(R_{50}=7.5$ cm) and the IAEA values used below have been taken from the erratum for Table 18 which gives $k_Q$ values.  

III. CHAMBER CONSTRUCTION

When simulating plane-parallel ionization chambers, detailed knowledge about chamber construction is essential. In some cases there are different versions of the same chamber that have been sold and the differences can be significant. In our study we used information provided by the manufacturers to simulate 10 different plane-parallel ionization chambers currently in clinical use. Some geometrical details were included in the calculations which were not considered in previous calculations.

Two of these chambers are homogeneous in their construction (Roos PTW 34001 and Holt NA 30-404). The material surrounding the cavity of the Exradin models A10 and P11 are air-equivalent and polystyrene-equivalent plastics (C552 and D400), respectively. But there are other materials present such as polycarbonate (Lexan) in the insulator, a Teflon piece and Delrin on the back of the body. The Markus chamber (model PTW 23343) generally considered as homogeneous, is actually made of PMMA with a 0.027 mm thick (2.5 mg/cm²) polyethylene entrance foil and a very thin graphite layer surrounding the air cavity. We also included PTW’s Advanced Markus chamber TN34045, which is similar to the Markus chamber, but with a smaller cavity. The major component material of the Attix chamber model 449 is Gammex/RMI solid water. It also has a 0.025 mm (4.8 mg/cm²) thick conducting Kapton film as the front wall and a 0.127 mm thick collecting polyethylene electrode. The PS-033 Capintec chamber is made mainly of polystyrene and it is provided with a 3.6 μm polyester film (Mylar®) as entrance window and an air equivalent plastic electrode (C552). The actual thickness of the C552 electrode for this chamber is not very well defined, although the manufacturer, Capintec Inc., states it is between 0.635 mm and 0.711 mm thick. Using EGS4/PRESTA Rogers reported that for 300 keV electrons there was no change in the backscatter for a C552 electrode thickness over 0.2 mm. In this work we investigated the influence of the electrode thickness on the response of the Capintec chamber to a $^{60}$Co beam using EGSnrc (see Sec. IV E). NACP chambers can be found in two slightly different models, types 01 and 02. Both models have a graphite body (back wall), a Rexolite® housing, a 0.2 mm thick graphited Rexolite® electrode and a 0.5 mm graphite entrance window. Type 02 has an extra 0.1 mm Mylar® foil over the front face. For a more detailed description of the chambers under study, the reader is referred to Table I and the manufacturer’s data sheets for these chambers.
Table I. Characteristics of plane-parallel chamber types modelled in this work. All dimensions are given in mm.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Materials</th>
<th>Cavity Radius sensitive</th>
<th>External Length</th>
<th>Radius</th>
<th>Window thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capintec</td>
<td>Mylar window, C552</td>
<td>2.4</td>
<td>12.7</td>
<td>18.0</td>
<td>0.0036</td>
</tr>
<tr>
<td>PS-033</td>
<td>electrode, polysty. body</td>
<td>(10.5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Markus</td>
<td>Polyethylene window</td>
<td>2.0</td>
<td>14.0</td>
<td>15.0</td>
<td>0.0269</td>
</tr>
<tr>
<td>PTW 23343</td>
<td>PMMA electrode and body</td>
<td>(3.0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced Markus</td>
<td>Polyethylene window</td>
<td>1.0</td>
<td>14.0</td>
<td>15.0</td>
<td>0.0269</td>
</tr>
<tr>
<td>PTW TN34045</td>
<td>PMMA electrode and body</td>
<td>(4.5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exradin</td>
<td>Kapton window</td>
<td>2.0</td>
<td>14.0</td>
<td>15.0</td>
<td>0.0272</td>
</tr>
<tr>
<td>Markus-type A10</td>
<td>C552 electrode and body</td>
<td>(7.11)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exradin</td>
<td>Polystyrene-equiv. plastic D400</td>
<td>10.0</td>
<td>17.45</td>
<td>22.25</td>
<td>1.0</td>
</tr>
<tr>
<td>Spokas P11</td>
<td>PMMA electrode and body</td>
<td>2.0</td>
<td>10.0</td>
<td>22.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Roos PTW 34001</td>
<td>PMMA electrode and body</td>
<td>(12.0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holt</td>
<td>Polystyrene</td>
<td>2.0</td>
<td>10.0</td>
<td>125.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Memorial</td>
<td>electrode and body</td>
<td>(17.5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attix</td>
<td>Kapton window, polyethylene electrode and SW body</td>
<td>1.0</td>
<td>14.0</td>
<td>30.0</td>
<td>0.025</td>
</tr>
<tr>
<td>RMI 449</td>
<td>graphite window and body</td>
<td>(20.0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NACP01</td>
<td>polyst. electrode</td>
<td>(8.0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scanditronix</td>
<td>Kapton window</td>
<td>2.0</td>
<td>10.0</td>
<td>15.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Scanditronix</td>
<td>graphite window and body</td>
<td>(8.0)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>mylar foil, polyst. electrode</td>
<td>(3.0)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

aTotal sensitive radius = guard ring width.

bThickness of extra protection cap for in-water measurements needed for some chambers not included. See Table V for details on water-proofing caps.

IV. RESULTS

A. General results

Table II presents the calculated values of various factors used in this work, viz., mass energy absorption coefficients \( \langle \mu_{en}/\rho \rangle_{med} \), Spencer–Attix stopping-power ratios \( \langle \bar{L}/\rho \rangle_{med} \), and the response for homogeneous ion chambers \( k_m \) (with \( K_{comp}K_{str} = 1 \)). No significant differences with EGS4 values were found, since stopping powers vary slowly with energy, and the major changes in the physics of EGSnrc only affect the condensed history implementation of electron transport and the transport of photons at lower energies. The average fraction of electron energy lost via radiative processes, \( g \), has been included in Table II since it is needed to calculate \( \langle \mu_{en}/\rho \rangle \) values from \( \langle \mu_{en}/\rho \rangle \) values. This quantity changes significantly for the different media, with a maximum difference of 57% between air and polyethylene. Nevertheless, these \( g \) values are considerably smaller than 1, so that there

<table>
<thead>
<tr>
<th>Medium</th>
<th>( \langle \mu_{en}/\rho \rangle_{med} ) ( [10^{-2} \text{ cm}^2 \cdot \text{g}^{-1}] )</th>
<th>( \bar{s}_{med} )</th>
<th>( \langle \bar{L}/\rho \rangle_{med} )</th>
<th>( k_m )</th>
<th>( \langle \bar{L}/\rho \rangle_{med} )</th>
<th>( \langle \mu_{en}/\rho \rangle_{med} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C552</td>
<td>2.6953</td>
<td>0.00299</td>
<td>0.9957</td>
<td>1.0054</td>
<td>1.0060</td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>2.6923</td>
<td>0.00307</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
<td></td>
</tr>
<tr>
<td>Graphite</td>
<td>2.6947</td>
<td>0.00254</td>
<td>1.0021</td>
<td>0.9988</td>
<td>0.9990</td>
<td></td>
</tr>
<tr>
<td>Kapton</td>
<td>2.7653</td>
<td>0.00260</td>
<td>1.0350</td>
<td>0.9924</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mylar</td>
<td>2.8071</td>
<td>0.00261</td>
<td>1.0526</td>
<td>0.9905</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>2.9942</td>
<td>0.00273</td>
<td>1.1332</td>
<td>0.9814</td>
<td>0.9800</td>
<td></td>
</tr>
<tr>
<td>PMMA</td>
<td>2.9099</td>
<td>0.00244</td>
<td>1.1018</td>
<td>0.9890</td>
<td>0.9820</td>
<td></td>
</tr>
<tr>
<td>RMISW</td>
<td>2.9115</td>
<td>0.00246</td>
<td>1.1116</td>
<td>0.9728</td>
<td>0.9710</td>
<td></td>
</tr>
<tr>
<td>Polystyrene</td>
<td>2.9012</td>
<td>0.00218</td>
<td>1.1102</td>
<td>0.9706</td>
<td>0.9710</td>
<td></td>
</tr>
<tr>
<td>Polyethylene</td>
<td>3.0781</td>
<td>0.00195</td>
<td>1.2077</td>
<td>0.9467</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE III. Calculated quantities for plane-parallel chambers free-in air with 0.5 g/cm² buildup caps of the main material of the ion chamber. Uncertainties in \(K_{\text{wall}}\) values are typically better than 0.01% and statistical uncertainties on calculated doses are below 0.04% and thus uncertainties on \(K_{\text{comp}}\) values are typically below 0.06%.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Cap</th>
<th>(K_{\text{comp}}) Eq. (9)</th>
<th>(K_{\text{wall}}) ((K_{\text{comp}}^\text{old})/K_{\text{comp}}^\text{new})</th>
<th>(k_m k_{\text{att}}) (K_{\text{wall}})</th>
<th>(k_m k_{\text{att}}) #&lt;sup&gt;9&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capintec</td>
<td>Polyst.</td>
<td>0.9955</td>
<td>0.9991</td>
<td>0.9982</td>
<td>0.9999</td>
</tr>
<tr>
<td>Markus</td>
<td>PMMA</td>
<td>0.9969</td>
<td>0.9998</td>
<td>0.9973</td>
<td>1.0003</td>
</tr>
<tr>
<td>Advanced</td>
<td>PMMA</td>
<td>0.9966</td>
<td>0.9994</td>
<td>0.9959</td>
<td>1.0001</td>
</tr>
<tr>
<td>Markus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extradin A10</td>
<td>C552</td>
<td>1.0051</td>
<td>0.9995</td>
<td>0.9930</td>
<td>1.0010</td>
</tr>
<tr>
<td>Extradin P11</td>
<td>Polyst.</td>
<td>0.9974</td>
<td>0.9989</td>
<td>0.9950</td>
<td>0.9994</td>
</tr>
<tr>
<td>Roos</td>
<td>PMMA</td>
<td>1.0000</td>
<td>1.0007</td>
<td>1.0032</td>
<td>1.0001</td>
</tr>
<tr>
<td>Holt</td>
<td>Polyst.</td>
<td>1.0000</td>
<td>0.9984</td>
<td>0.9891</td>
<td>1.0004</td>
</tr>
<tr>
<td>Attix</td>
<td>RMISW</td>
<td>1.0166</td>
<td>0.9988</td>
<td>0.9910</td>
<td>1.0005</td>
</tr>
<tr>
<td>NACP01</td>
<td>Graph</td>
<td>1.0243</td>
<td>0.9997</td>
<td>0.9971</td>
<td>1.0014</td>
</tr>
<tr>
<td>NACP02</td>
<td>Graph</td>
<td>1.0249</td>
<td>0.9998</td>
<td>0.9974</td>
<td>1.0014</td>
</tr>
</tbody>
</table>

*Ratio of \(K_{\text{comp}}\) value calculated using Spencer–Attix theory [Eq. (6)] and using the dose ratio method [Eq. (9)]. This ratio is equivalent to the value of \(K_{\text{comp}}\) for a homogeneous chamber made of the material of the buildup cap when using Spencer–Attix theory to calculate \(K_{\text{comp}}\).

*Present calculation showing differences from definitions only = \(K_{\text{wall}}^\text{real,pt}/K_{\text{wall}}^\text{real,in-air}\). Previously calculated values of \(K_{\text{comp}}\) must be multiplied by these values to have a common definition.

is only a small difference in the numerical value of \((1 - \bar{g})\). The \(\bar{g}\) values were calculated with AE=0.512 MeV and AP=0.001 MeV. For the \(^{60}\)Co spectrum used in this work, a value of \(4.5525 \times 10^{-12} \text{ Gy cm}^2\) was obtained for \(K_{\text{air}}(1 - \bar{g})\), the collision air kerma per unit fluence in the beam. This is 0.03% lower than the value used previously.<sup>20</sup>

### B. \(K_{\text{comp}}\) results

Table III presents the values of \(K_{\text{comp}}\) and \(K_{\text{wall}}\) calculated in this work for buildup caps made of the major material in the chamber. Column 6 presents the ratio of \(K_{\text{wall}}\) values calculated in this work according to the present definition vs the previous definition, i.e., \(K_{\text{wall}}^\text{homo,pt}/K_{\text{wall}}^\text{homo,in-air}\). The previously calculated values of \(K_{\text{comp}}\) need to be multiplied by this factor [see Eq. (8)] to correspond to the same definition of \(K_{\text{comp}}\). This ratio is very close to unity in most cases, and is always within 0.14% of unity. The largest differences are for the NACP chamber where the difference between the attenuation and scatter in the graphite and other materials is most significant. Since these values are close to unity, the previously calculated values of \(K_{\text{comp}}\) and \(P_{\text{wall}}\) were not significantly affected by the omission of this factor. Column 4 presents the ratio of \(K_{\text{comp}}\) values calculated either as the ratio of calculated doses to air [Eq. (9)] or using Spencer–Attix cavity theory and Eq. (6). Algebraically, it can be shown that the ratio in column 4 also corresponds to the value of \(K_{\text{comp}}\) for the homogeneous chamber calculated using the Spencer–Attix approach. In either case, it is reassuring that the average of the 10 values in the column is 0.9994 with a sample deviation of 0.0006. This indicates that the EGSnrc calculations and Spencer–Attix cavity theory as applied here are consistent at better than the 0.1% level. Column 7 presents the values of \(K_{\text{wall}}\) for these plane-parallel chambers at 80 cm from a point source. This correction has a typical value near 1.002 which corresponds to moving a chamber about 0.8 mm closer to the point source to get the same reading as from a parallel beam. Column 8 presents the values of \(k_m k_{\text{att}}\) for these chambers based on Eq. (11).

Figure 2 presents a comparison of the present \(K_{\text{comp}}K_{\text{att}}\) values with previous calculations using EGS4/PRESTA<sup>23</sup> which reported \(K_{\text{comp}}\) values corresponding to \(K_{\text{comp}}K_{\text{att}}\) values here. The EGS4/PRESTA calculations are systematically lower than the present results differing on average by 0.8% with differences ranging from 0.6% up to 1.4%. Figure 2 also shows experimental data from Laitano et al.,<sup>14</sup> Kuchnir and Reft,<sup>12</sup> Mattson et al.,<sup>8</sup> and Kubo.<sup>10,11</sup> In all cases the present results are in closer agreement to measurement than the EGS4/PRESTA calculations although the large experi-

![FIG. 2. Comparison of calculated and measured \(K_{\text{comp}}K_{\text{att}}\) values using solid buildup caps (in-air calibration) made of the chamber’s predominant material. EGSnrc values are represented by solid up triangles and previous EGS4/PRESTA calculations (Ref. 23) with solid diamonds. Previous values were originally presented as \(K_{\text{comp}}\) but as discussed in the text, are actually \(K_{\text{comp}}K_{\text{att}}\). The experimental data sets from Laitano et al. (Ref. 14) (open squares), Kuchnir and Reft (Ref. 12) (open circles), Mattson et al. (Ref. 8) (open triangles) and Kubo (Refs. 10 and 11) (stars) are also included.]()
mental uncertainties make definitive conclusions impossible.

Based on Monte Carlo and experimental data, Rogers recommended values, some of which were adopted in IAEA TRS-381. As can be seen from Fig. 3, EGSnrc derived values are in better agreement with those recommended values than with the most recent EGS4/PRESTA calculations. Several experimental data sets are also included for comparison. Column eight of Table III also shows the calculated values of $k_{\text{att}}$.

### C. Equivalence of $K_{\text{comp}}$ and $P_{\text{wall}}$

Table IV presents values of $K_{\text{comp}}$ calculated free-in-air using the ratio of doses method, Eq. (9), and values of $P_{\text{wall}}$ calculated using the same method, Eq. (10), but at 5 cm depth in a water phantom irradiated by a 100 cm$^2$ field. Column 4 gives the ratios of the values of $K_{\text{comp}}$ to $P_{\text{wall}}$ and it is clear that at the 0.1% statistical precision of these calculations, the two methods give identical results, thereby justifying the assumptions used in previous publications and justifying the use of much shorter calculations of $K_{\text{comp}}$ to give $P_{\text{wall}}$ values for other chambers.

Although the above justifies the previous assumption that $K_{\text{comp}} = P_{\text{wall}}$, it should be noted that in practice, the previous calculations were assigning $P_{\text{wall}} = K_{\text{comp}}k_{\text{att}}$ which is conceptually slightly incorrect, but well within the earlier systematic uncertainty of 1%.

### D. $P_{\text{wall}}$ values in-phantom

Table V presents values of $P_{\text{wall}}$ for the plane-parallel ion chambers when irradiated in a water phantom by a $^{60}$Co beam.

---

**Table IV.** Comparison of calculated values of $K_{\text{comp}}$ for a water buildup cap and $P_{\text{wall}}$ values calculated at 5 cm depth in a water phantom. Statistical uncertainties on individual doses are typically 0.04% and 0.06% for in-air and in-phantom calculations, and thus uncertainties on ratios (columns 2, 3) are typically 0.06% and 0.08%, respectively, and on the ratio of ratios (column 4) it is about 0.1%.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>$K_{\text{comp}}$</th>
<th>$P_{\text{wall}}$</th>
<th>$K_{\text{comp}}/P_{\text{wall}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roos</td>
<td>1.0090</td>
<td>1.0087</td>
<td>1.0003</td>
</tr>
<tr>
<td>Attix</td>
<td>1.0314</td>
<td>1.0307</td>
<td>1.0007</td>
</tr>
<tr>
<td>NACP02</td>
<td>1.0207</td>
<td>1.0204</td>
<td>1.0003</td>
</tr>
</tbody>
</table>

*For a water buildup cap.

**Table V.** Values of $P_{\text{wall}}$ for $^{60}$Co beams incident on a water phantom as determined by taking $P_{\text{wall}} = K_{\text{comp}}$ for an ion chamber irradiated free-in-air with a buildup cap of water. The values are calculated as the ratio of calculated doses [Eq. (6)]. A waterproofing slab of the major material has been added unless the chamber has its own waterproof front face. This is indicated explicitly in the second column. Total thickness of waterproofing cap and water cap is 0.5 g/cm$^2$. The IAEA’s TRS-398 does not use $k_{\text{ecal}}$ explicitly, but $k_{\text{ecal}} = k_{\text{cal}}(R_{50} = 7.5 \text{ cm})$ and the IAEA values have been taken from the erratum for Table 18 (Ref. 6). The values for the Capintec chamber correspond to an electrode thickness of 0.711 mm. Statistical uncertainty on $P_{\text{wall}}$ values is less than 0.06% in all cases.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Water proofing</th>
<th>$P_{\text{wall}}$</th>
<th>AAPM TG-51 (Ref. 5)</th>
<th>IAEA 2001 (Ref. 6)</th>
<th>Present</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capintec</td>
<td>1.00 mm polystyrene</td>
<td>0.9861</td>
<td>0.921</td>
<td>0.907</td>
<td>0.917</td>
</tr>
<tr>
<td>Markus</td>
<td>0.87 mm PMMA</td>
<td>1.0048</td>
<td>0.910</td>
<td>0.892</td>
<td>0.899</td>
</tr>
<tr>
<td>Advanced Markus</td>
<td>0.87 mm PMMA</td>
<td>1.0082</td>
<td>0.909</td>
<td>0.895</td>
<td>0.896</td>
</tr>
<tr>
<td>Extradin A10</td>
<td>1.00 mm PMMA</td>
<td>0.9621</td>
<td>0.888</td>
<td>0.888</td>
<td>0.879</td>
</tr>
<tr>
<td>Extradin P11</td>
<td>1.0280</td>
<td>0.888</td>
<td>0.888</td>
<td>0.879</td>
<td></td>
</tr>
<tr>
<td>Roos</td>
<td>1.0090</td>
<td>0.901</td>
<td>0.895</td>
<td>0.896</td>
<td></td>
</tr>
<tr>
<td>Holt</td>
<td>1.0104</td>
<td>0.900</td>
<td>0.890</td>
<td>0.894</td>
<td></td>
</tr>
<tr>
<td>Attix</td>
<td>1.00 mm RMI solid water</td>
<td>1.0314</td>
<td>0.883</td>
<td>0.884</td>
<td>0.876</td>
</tr>
<tr>
<td>NACP01</td>
<td></td>
<td>1.0216</td>
<td>0.888</td>
<td>0.885</td>
<td></td>
</tr>
<tr>
<td>NACP02</td>
<td></td>
<td>1.0207</td>
<td>0.883</td>
<td>0.885</td>
<td></td>
</tr>
</tbody>
</table>
The 60 Co in-phantom method, described in the AAPM TG-39 protocol, 3 to obtain \( P_{\text{wall}} \) but using two different dosimetry systems and electron accelerators. They determined \( P_{\text{wall}} \) values in water phantoms for the Markus and the NACP02 plane-parallel chambers (open triangles in Fig. 4). Their values are higher than ours, although our data lie within their reported uncertainty of 1.5%.

Palm et al. 38 used the two different methods discussed in the introduction to determine \( P_{\text{wall}} \). In Fig. 4 the result for the Roos chambers using the procedure which is independent of the calibration standard is represented by the upper star (1.0% reported uncertainty) and the result of the second method is represented by the lower star (1.5% reported uncertainty). Our \( P_{\text{wall}} \) value for the Roos chamber is well within the error bars for both measurements as is our value for the NACP02 chamber.

Recently Stewart and Seuntjens 40 obtained \( P_{\text{wall}} \) values in a water phantom for the Markus, Roos and NACP02 plane-parallel ionization chambers by cross calibration against a cylindrical ionization chamber in a 60 Co and a 20 MeV electron beam. Their data were processed using both the AAPM TG-51 and the IAEA TRS-398 protocols (open crossed diamonds in Fig. 4). Our calculated values are within their error bars for all their results.

In the last three columns of Table V \( k_{\text{ecal}} \) values obtained in this work are summarized and compared with those calculated by Rogers 33 and recommended in AAPM TG-51 3 and with \( k_{\text{ecal}} \) values derived using the \( k_{\Omega} \) values in Table 18 of the IAEA TRS-398 Code of Practice. 8 These are virtually the same as the TG-51 values for the Attix, Exradin and Holt chambers since the IAEA used the same \( P_{\text{wall}} \) values as the AAPM’s TG-51 for these chambers. The present results tend to split the difference between the TRS-398 and TG-51 values, except for the Attix chamber where the present value is 0.7% less than both of them.

### E. Influence of electrode thickness on the response of the Capintec chamber PS-033

We calculated the dose to the air in the cavity of a Capintec chamber varying the C552 electrode thickness from 0 up to 1 mm using both a polystyrene and a water buildup cap (AE=ECUT=10 keV). Figure 5 shows that the dose to the air in the cavity relative to the dose to the air without a C552 electrode increases nonlinearly with electrode thickness up to 0.7 mm and thereafter a saturation is observed. The uncertainty in the electrode thickness between 0.635 mm and 0.711 mm implies an uncertainty in the calculated response of 0.06%. These results confirm the earlier conclusion that backscatter from the electrode material is critical to understanding the large values of \( K_{\text{comp}} \), but these are much more detailed calculations which show a quantitatively different dependence on the electrode thickness.
F. Effect on $K_{\text{wall}}$ and $K_{\text{comp}}$ of uncertainty in cross sections

1. Photon cross sections

Papers devoted to the compilation of photon cross-sections report uncertainties to be around 1% in the energy region dominated by the Compton interaction for light elements.\(^{41-43}\) However, taking into account that the most significant part of the $^{60}\text{Co}$ spectrum lies between 200 keV and 1.335 MeV, where binding effects in low-Z materials are negligible, the uncertainties are most likely smaller since the Compton scattering process can be very closely described using the free-electron scattering approach.

Nonetheless, we have studied the influence of hypothetical changes in the total photon cross section on the $K_{\text{comp}}$ and $K_{\text{wall}}$ correction factors. First the photon cross section was changed in 1% steps up to 20% for an Exradin P11 ionization chamber, simulated as homogenous polystyrene. No significant changes in $K_{\text{wall}}$ could be observed within statistical uncertainties which were typically 0.03%. Since the uncertainty in photon cross sections is larger at low energies, the next step was to decrease the photon cross section change logarithmically with increasing energy, with a maximum change of 10% at the minimum photon energy. As in the previous case, no significant changes were observed. For this chamber, since $K_{\text{comp}}=1.0$, the cross-section uncertainty has no effect on $K_{\text{comp}}$.

To study the effect for a chamber in which $K_{\text{comp}}$ was not unity, we changed the photon cross section for graphite by 1% to investigate the effect on an NACP02 chamber. The photon cross section for polystyrene was left unchanged. There was a 0.1% change in $K_{\text{comp}}$ and a 0.02% change in $K_{\text{wall}}$. If the photon cross sections for graphite and polystyrene were changed in opposite directions by 1%, (0.2\% and (0.04\%\pm0.01)\%) increases in $K_{\text{comp}}$ and $K_{\text{wall}}$ were observed.

For most of the plane-parallel ionization chambers the $K_{\text{wall}}$ correction factor is close to unity, thus we repeated the same study for the 3C, a cylindrical ion chamber which is the basis of Canada’s primary standard for air-kerma. This chamber requires larger $K_{\text{wall}}$ corrections ($\approx1.02$), but nonetheless produced a similar outcome, i.e., a 0.12% change in $K_{\text{comp}}$ and a 0.007% change in $K_{\text{wall}}$. In the extreme case of increasing by 1% the graphite photon cross section and reducing by 1% the polystyrene photon cross section, in the extreme case of increasing by 1% the graphite photon cross section and reducing by 1% the polystyrene photon cross section, change of 0.2% and 0.008% on $K_{\text{comp}}$ and $K_{\text{wall}}$ were observed.

The uncertainty on $K_{\text{comp}}$ and $P_{\text{wall}}$ from the 1% uncertainty in the photon cross sections is taken as 0.14% and on $K_{\text{wall}}$ is taken as 0.03% (summing in quadrature the effects of changing individual cross sections by 1%). There should be a negligible uncertainty on $K_{\text{ann}}$ from this cause.

2. Electron stopping powers

In this section we investigate the effect of reported uncertainties in $I$, the mean ionization energy, and therefore in the stopping powers, on the correction factors for an NACP02 plane-parallel ionization chamber. This chamber is mainly made of graphite and polystyrene. Different data sets were created for these media using the PEGS4 input option of entering an $I$ value different from the default PEGS4 value.

The uncertainties in the $I$-values stated in ICRU Report 37\(^2\) are figures of merit which can be interpreted as two standard deviations uncertainties. For graphite and polystyrene the estimated uncertainty in the $I$ value in ICRU-37 can be translated into 4.5% and 2.0% one standard deviation uncertainties, respectively. A rigorous study of the effect of these uncertainties on the correction factors, that considers all the possible combinations would require randomly sampling a large number of $I$ values, creating corresponding PEGS4 data sets, doing Monte Carlo calculations using these data sets and finally, estimation of the average effect on the quantities of interest. This is clearly not practical and therefore we chose to propagate the effect of the reported one standard deviation uncertainties in the $I$ values for polystyrene and graphite.

Since $K_{\text{comp}}, K_{\text{ann}},$ and $K_{\text{wall}}$ are ratios of doses in the air cavity, we expect no changes in their values due to uncertainties in the $I$ value for air. To prove this, we increased the $I$ value for air by 5% and observed no variation in these quantities within the statistical uncertainties of 0.1%, 0.1%, and 0.03% for $K_{\text{comp}}, K_{\text{ann}},$ and $K_{\text{wall}}$, respectively.

Changing the graphite $I$ value by 4.5% causes an average change in $K_{\text{comp}}$ of 0.22%. Similar changes in the polystyrene $I$ value of 2.0% gives a 0.1% change in $K_{\text{comp}}$. In the worst case of a 4.5% decrease in the graphite $I$ value and a 2.0% decrease or increase in the polystyrene $I$ value, a 0.3% reduction in the $K_{\text{comp}}$ value is observed. A reasonable way to assess the uncertainty in $K_{\text{comp}}$ due to these uncertainties in the $I$ values is to add them in quadrature to give an overall uncertainty of 0.24%. Note that this analysis has not taken into account the uncertainty induced by the uncertainty in the density effect correction used to calculate the stopping powers. This is ignored since it is much smaller than the uncertainty from the $I$ values (the largest density-effect uncertainty is for graphite, but for graphite the uncertainty in the $I$ value is even larger).

Within a statistical uncertainty of 0.02% at the one standard deviation accuracy level, no significant change in $K_{\text{wall}}$ is observed for these different $I$ values for the stopping powers. Similarly, the value of $K_{\text{ann}}$ should not depend on the electron stopping powers since it is the ratio of two calculations for the same materials and cavity.

3. Overall uncertainties on calculated corrections

The statistical uncertainties in the calculated doses to obtain $K_{\text{comp}}, K_{\text{ann}},$ and $P_{\text{wall}}$ are below 0.04% and thus the statistical uncertainty on these quantities, which are the ratio of two doses, is 0.06% or less. The statistical uncertainty on $K_{\text{wall}}$ values is about 0.01%.

Adding in quadrature the uncertainties due to cross-section uncertainties discussed above and these statistical uncertainties, the overall uncertainties for the factors $K_{\text{wall}}, K_{\text{comp}},$ and $K_{\text{ann}}$ are 0.03%, 0.29%, and 0.06%, respectively. These uncertainties contain no component due to the ac-
curacy of the EGSnrc code itself (0.1% or better, excluding cross-section uncertainties) because all the corrections have been calculated as ratios of dose to air calculations. This is a considerable improvement over previous calculations which had a 1% uncertainty from consideration of the accuracy of EGS4/PRESTA. However, if the previous calculations had used the ratio of doses method used here, the uncertainty would have been considerably less.

These uncertainties also ignore the uncertainties due to variations between individual chambers and the models of them that were used for the calculations. These latter uncertainties may dominate the actual uncertainty.

V. SUMMARY AND CONCLUSIONS

It has been shown that the correction for the axial non-uniformity of the beam, $K_{an}$, must be taken into account to get proper consistency in the various calculations. This effect is about 0.2% and corresponds to moving the plane parallel chambers about 0.8 mm closer to the source to get the same response as if in a parallel beam. Previous work, which ignored this factor, was always using the product $K_{comp}K_{an}$ for in-air applications so that this error made no difference for these applications. However, it does mean that the previous calculated values of $P_{wall}$ were erroneously set equal to $K_{comp}K_{an}$ and were thus 0.2% too large an average, well within the previous systematic uncertainty of 1%. 20, 23

In addition, in order for the value of $K_{comp}$ in air to be fully equivalent to the $P_{wall}$ correction needed in phantom, it was found necessary to redefine slightly the correction for wall attenuation and scatter [see Eqs. (5) and (7)]. This also implies that the previous values of $K_{comp}$ need to be corrected [see Eq. (8)] but with the exception of the NACP chambers, where this amounts to a 0.14% increase in $K_{comp}$, the change is less that 0.1%, and what effect there is tends to cancel the larger $K_{an}$ effects.

The near unity values of $K_{comp}$ calculated for homogeneous chambers (Table III, column 4) show that the improvements in EGSnrc calculations mean calculations regarding the response of ion chambers in a $^{60}$Co beam produce results consistent with Spencer–Attix cavity theory at the 0.06% accuracy level. This is a remarkable degree of consistency which further confirms the accuracy of EGSnrc at the 0.1% level, and also confirms the applicability of Spencer–Attix cavity theory at this level of accuracy.

Despite the fact that reported experimental data sets have large inherent uncertainties, a comparison of these measurements with calculations shows that most of the present EGSnrc values lie closer to the experimental values than those obtained earlier with EGS4/PRESTA.

An investigation of the appropriate low-energy cutoff to use in these ion chambers showed that it was definitely less than 10 keV, but this is at most a 0.36% effect. This is important when obtaining consistency with Spencer–Attix cavity theory, but has a negligible effect on the factors calculated as dose ratios.

Calculations performed for the Roos, Attix, and NACP chambers in a water phantom demonstrate the accuracy of the assumption that $K_{comp} = P_{wall}$ at the 0.06% level, where $K_{comp}$ is calculated for the chamber with a water buildup cap, free-in-air.

Values of $K_{comp}$ and $P_{wall}$ obtained by previous EGS4/PRESTA calculations are systematically lower than the current values obtained using EGSnrc. For the case of calibrations in air an average deviation of 0.8% was obtained (comparing $K_{comp}$ $K_{an}$ values now to the corresponding values, reported as $K_{comp}$ previously) and, for calibrations in water phantoms the average difference is also 0.8%. In the latter case, the comparison is for the reported values but, as discussed above, there are actually differences in the definitions of the quantities in the two papers.

We have presented an uncertainty analysis which concludes that the overall uncertainty on the factors $K_{wall}$, $K_{comp}$, and $K_{an}$ are 0.03%, 0.29%, and 0.06%, respectively. These include uncertainties due to the cross-section data and other systematic uncertainties (which are small because of the ratios used in all calculations now). This suggests that these calculated values are now much less uncertain than any of the measured values. However, these uncertainties ignore the uncertainties due to variations between individual chambers and the models of them that were used for the calculations. It is for this reason that one should still use cross calibrations of plane-parallel chambers as recommended by protocols and codes of practice.

ACKNOWLEDGMENTS

We wish to thank our NRCC colleague Ken Shortt for his invaluable help regarding the design of the plane-parallel ionization chambers and for stimulating discussions on the subject. We also want to acknowledge our sincere gratitude to Christian Pychlau from PTW-Freiburg for updated information on the Markus chamber, Mark Marsico from Scanditronix–Wellhofer North America for information on the NACP chambers, Brian Hooten from Standard Imaging for his detailed information on the Exradin P11 and A10 models and Capintec Inc. who so kindly provided us with details of the chamber’s construction. Our special thanks to Jan Seuntjens and Kristen Stewart who graciously gave us access to their (then) unpublished results.

1Electronic mail: mainegra@irs.phy.nrc.ca


