LETTER TO THE EDITOR

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LETTER TO THE EDITOR

Comments on ‘Ionization chamber volume determination and quality assurance using micro-CT imaging’

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Abstract

The authors of a recent paper (McNiven et al 2008 Phys. Med. Biol. 53 5029–43) measured the volume of a particular type of a small ionization chamber using CT images. Using four Exradin A1SL chambers, they find that the volume measured using CT imaging is, on average, 4.3% larger than the value derived from the chamber calibration coefficient. Although they point out that the effective chamber volume is defined by electric field lines between the collector and the chamber body, they do not estimate how the mechanical volume might differ from the effective volume. We have used a commercial software package to calculate the electric field in the cavity and we show that the field lines define a volume that is about 11% smaller than the mechanical volume. We also show that the effective volume is very sensitive to small changes in the chamber geometry near the base of the collector. We conclude that simply determining the mechanical volume without careful consideration of the electric field lines within the cavity is not a useful dosimetric technique.

1. Introduction

In a recent paper, McNiven et al (2008) used micro-CT imaging to determine the cavity volume and to study structural defects in the Exradin A1SL ionization chamber. The A1SL is a small cylindrical chamber constructed from C552 air-equivalent plastic having a nominal sensitive volume of 56 mm³, according to the manufacturer’s specifications.

The micro-CT device produces images with a spatial resolution of about 0.02 mm, and software can be used to identify the interfaces between air and C552. A plane is introduced to define the limit of the cavity at the base of the collector and the resulting air volume is determined with a standard uncertainty of less than 1%. Although the authors recognize that the sensitive volume will be defined by the electric field lines, they make no effort to
estimate how the sensitive volume will differ from the mechanical volume. We show that the difference is so large for the A1SL chamber that it calls into doubt the authors’ claim that ‘the results demonstrate the promise of using micro-CT imaging for the absolute volumetric characterization of ion chambers’.

2. Analysis

The electrostatic potential, $\Phi$, in a charge-free region is given by the solution of the Laplace equation,

$$\nabla^2 \Phi = 0,$$

subject to the boundary conditions imposed by the voltages applied to the conducting surfaces of the ionization chamber. We used the commercial software package, FlexPDE (www.pdesolutions.com), to solve for the potential distribution within the cavity. FlexPDE is script-driven and uses the finite element technique to solve differential equations. It takes about 20 s to generate the potential distribution in the chamber cavity on a present-day PC.

Cylindrical symmetry was assumed, but otherwise the chamber geometry as shown in figure 1 was accurately simulated. The precise chamber dimensions used for the simulations were taken from a drawing, kindly provided by Brian Hooten of Standard Imaging, and gave a calculated chamber volume of 63.3 mm$^3$.

Once the potential distribution is known, the electric field can be obtained using

$$\vec{E} = -\nabla \Phi.$$

Charged particles move in response to the electric field and follow the field lines which are defined such that the electric field vector is tangent to the field line at each point in space. Representative electric field lines are shown near the base of the A1SL chamber in figure 2. As required by the boundary conditions, an electric field line always meets a conducting surface.
at right angles. The solid line shows the field line that bisects the gap between the collector and the guard. This line defines the boundary between the region where ions will be transported to the collector and the region where they will end up on the guard. The difference between the mechanical volume as defined by McNiven et al and the sensitive volume is represented by the three-dimensional region lying to the right of this line and delimited on the bottom by a plane coincident with the top surface of the guard.

The volume of this region can be determined by noting that the elementary cylindrical volume at radius $r$ and of height $z$ is given by $2\pi r \, dr \cdot z$. The total volume can be found by integrating this quantity from the centre of the insulating gap to the chamber wall, where the field line is used to determine $z$ for each value of $r$. Using the trapezoidal rule, the volume was found to be 6.69 mm$^3$ or 10.6% of the total volume.

The drawing of the A1SL that is included with the specifications indicates that the step at the bottom of the collector and the top surface of the guard are in the same plane. However, the CT images presented by McNiven et al indicate that the step on the collector is slightly above the guard. We estimate from their images that the difference is about 0.15 mm, so we have repeated the electric field calculations for this situation as well as the case in which the guard is 0.15 mm higher than the step on the collector. We find that the difference between the mechanical volume and the sensitive volume is 8.0% when the guard is low and 13.3% when it is high, or a change of about 1.8% per 0.1 mm.

The authors compare the volume measured using micro-CT to the result obtained using cavity theory, which gives the volume from which ions are collected. If $D_{w,Q}$ denotes the absorbed dose to water and $N_{D,w,Q}$ the absorbed dose to water calibration coefficient for beam quality, $Q$, then

$$D_{w,Q} = M \cdot N_{D,w,Q} = \frac{M \cdot K_h}{\rho \cdot V} \cdot \frac{W}{e} \cdot s_{w,\text{air}} \cdot p_Q,$$

Figure 2. Plot of representative field lines near the base of the A1SL chamber. The field line represented by the solid line marks the boundary between the regions where ions are transported to either the central electrode or the guard. The volume to the right of this field line is not part of the sensitive volume of the chamber.
where the notation of the IAEA dosimetry protocol, TRS-398, is followed (Andreo et al. 2000). In particular, $M$ is the charge measured in response to irradiation, $K_h$ is the humidity correction factor, $\rho$ is the density of air, $V$ is the cavity volume, $W/e$ is the average energy per unit charge required to create ion pairs, $s_{w, \text{air}}$ is the ratio of restricted electron stopping powers of water to air and $p_Q$ is a product of correction factors. For $^{60}$Co $\gamma$-rays, TRS-398 gives a value of 1.100 for $s_{w, \text{air}} \cdot p_Q$ for the Exradin A1 chamber which has the same cavity properties as the A1SL. The consensus value for $W/e$ is 33.97 J C$^{-1}$ and the density of air is 1.196 kg m$^{-3}$ under the calibration reference conditions of 22 °C and 101.3 kPa, as used in North America. Note that $N_{D,w,Q}$ is assumed to be the calibration coefficient appropriate for humid air.

Equation (3) can be rewritten as

$$D_{w,Q} = M \cdot N_{D,w,Q} = M \cdot K_h \cdot N_{\text{gas}} \cdot s_{w, \text{air}} \cdot p_Q,$$

where $N_{\text{gas}}$ is what is referred to as the cavity–gas calibration factor in the TG-21 protocol of the American Association of Physicists in Medicine (Schulz et al. 1983), and is given by

$$N_{\text{gas}} = \frac{W/e}{\rho \cdot V}.$$  

McNiven et al compute an equivalent value of $N_{\text{gas}}$ for the mechanical volume and they compare the dosimetric and micro-CT values of $N_{\text{gas}}$ in their table 1. They also plot the mechanical volumes for the four chambers in their figure 3. (We note an inconsistency between the two data sets, with the volumes in figure 3 being, on average, 1.2% smaller than those calculated using the values of $N_{\text{micro-CT}}$ given in table 1.) They find that, on average, the mechanical volume is 4.3% larger and conclude ‘That this is good agreement...’ However, we show that the mechanical volume is expected to be 8.0% greater than the sensitive volume, which suggests that the mechanical volume the authors have measured is too small by about 3.7%. (This becomes 4.9% if one uses the values from figure 3 rather than table 1.)

The Accredited Dosimetry Calibration Laboratory (ADCL) at the University of Wisconsin has calibrated a large number of A1SL chambers using $^{60}$Co $\gamma$-rays and reports a mean value of 56.4 cGy nC$^{-1}$ for the absorbed dose to water calibration coefficient, $N_{D,w,\text{Co}}$, and a distribution of values corresponding to a standard deviation of 2.3%. Given $N_{D,w,\text{Co}}$, equation (3) can be solved for the chamber volume and the result is 55.2 mm$^3$. If we assume that the collector and guard are offset in all A1SL chambers as it is for the chamber shown in figure 2 of McNiven et al, then the mechanical volume would be expected to be 8.0% larger than the sensitive volume, or 59.6 mm$^3$. This result is within 1.2% of the average chamber volume obtained using the data in figure 3.

This agreement may be fortuitous as chamber-to-chamber variations may lead to significant differences in the chamber calibration coefficients. McNiven et al do not give values of $N_{D,w,\text{Co}}$ for their chambers but they can be derived from their values for the cavity–gas calibration factor, $N_{\text{gas}}$, using equation (4). The average value of $N_{D,w,\text{Co}}$ for the four chambers is 53.3 cGy nC$^{-1}$, a result that is 5.5% lower than the Wisconsin value. The distribution of values measured by the Wisconsin ADCL has a standard deviation of 2.3%, so the McNiven et al chambers lie well out in one of the tails of this distribution.

3. Conclusions

McNiven et al used micro-CT to determine the mechanical volume of an ionization chamber. However, they failed to carry out a quantitative analysis of how the electric field in the cavity would affect the relationship between the mechanical volume and the sensitive volume. We show that the differences are very large and are sensitive to subtle changes in the geometry of
the chamber. We also show that the mechanical volume the authors measure is too small by a few per cent, opposite to what they conclude. It is doubtful that using micro-CT to estimate the mechanical volume of small ionization chambers similar to the design of the A1SL is helpful for dosimetry based on these detectors. There may be other chamber designs where it could prove useful but first, one must establish the accuracy with which micro-CT can measure small volumes.

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References

