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Extracting W_{air} from the electron beam measurements of Domen and Lamperti

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Abstract

Purpose The average energy expended by an energetic electron to create an ion pair in dry air, W_{air} , is a key quantity in radiation dosimetry. The data obtained by Domen and Lamperti [Med. Phys. **3**, 294–301 (1976)] using electron beams in the energy range from 15 to 50 MeV can be used to deduce values for W_{air} , if the electron stopping power of graphite and air are known. Previous analysis of these data revealed an anomalous variation of 2% in W_{air} as a function of the electron energy. We propose to use Monte Carlo simulation techniques to re-analyze the original data and obtain new estimates for W_{air} , and to investigate the source of the reported anomaly.

Method Domen and Lamperti (DL) reported the ratio of the response of a graphite calorimeter to that of a graphite ionization chamber for broad beams of electrons with energies between 15 and 50 MeV and at different depths in graphite (including depths well beyond the range of the primary electrons, i.e., in the bremsstrahlung photon regime). Using a detailed EGSnrc model of the DL apparatus, as well as up-to-date stopping powers, we compute the dose ratio between the ionization chamber cavity and the calorimeter core, for plane-parallel electron beams. This dose ratio, multiplied by the DL data, provides a direct estimate for W_{air} .

Results Despite an improved analysis of the original work, the extracted values of W_{air} still exhibit a definite increase as the mean electron energy decreases below about 15 MeV (at the point of measurement). This anomalous trend is dubious physically, and inconsistent with extensive data for W_{air} obtained at lower energies. A thorough sensitivity analysis indicates that this trend is unlikely to stem from errors in extrapolation and correction procedures, uncertainties in electron stopping powers, or bias in calorimetry or ionization chamber measurements. However, we find that results are quite sensitive to the intrinsic graphite mass thickness of the detectors and to the incident beam energy.

Conclusion The DL experiment provides data in an energy regime where the electron stopping power is insensitive to the mean excitation energy of graphite—an issue plaguing W_{air} experiments at lower energies. Unfortunately, state-of-the-art scrutiny of the original data cannot explain the anomalous trend in terms of perturbation effects or extrapolation bias. It can only be understood in terms of speculative offsets in graphite mass thickness or beam energy.

This precludes using the DL data to narrow the uncertainty on W_{air} values beyond the currently accepted range: (33.97 ± 0.11) eV. Therefore higher accuracy measurements for electron energies above 15 MeV are recommended to further resolve the value of W_{air} .

keywords: average energy to create an ion pair, graphite calorimeter, ionization chamber, megavoltage electrons, EGSnrc, electron stopping powers

1 Introduction

Air-filled ionization chambers are widely used for measuring ionizing radiation fields. In many cases, relative measurements suffice; but any absolute measurement of air kerma or absorbed dose requires knowledge of W_{air} , the mean energy expended by an energetic electron to create an ion pair in air. It is a fundamental quantity in radiation dosimetry, first alluded to by Thomson and Rutherford in a 1896 paper,¹ notably “*this being still a year ahead of the discovery of the electron*”.² For electrons with an energy less than about 10 keV, it is possible to measure W_{air} directly using a total absorption technique.³ As the electron energy increases further, the value of W_{air} is expected to converge towards a high-energy limit, and the best data in this regard has been obtained by comparing the response of a graphite calorimeter and a graphite ionization chamber in ^{60}Co γ -ray beams.⁴ This approach requires knowledge of the electron stopping power for graphite (and for air), which poses a challenge because of uncertainties related to the mean excitation energy of graphite, I_g , and to the appropriate density effect correction. In addition, recent work⁵ has pointed out that the perturbation correction previously ascribed to the graphite ionization chamber by Niatel *et al.*⁴ is incorrect. Burns⁶ has re-analyzed the available data on I_g , W_{air} and the product $W_{\text{air}} \cdot s_{g,\text{air}}$ (where $s_{g,\text{air}}$ is the graphite to air stopping power ratio), to conclude that the best consistency overall is obtained when $W_{\text{air}} = (33.97 \pm 0.11)$ eV.

Remarkably, increasing the electron energy further in the MeV domain mitigates these uncertainties: the stopping power becomes relatively independent of I_g , and accurate electron stopping power measurements in the 5–30 MeV range have resolved the density effect issue.⁷ Hence, deriving W_{air} from measurements at higher energy is in principle more robust and provides an independent verification of its value over the whole energy range of interest in radiation therapy.

In 1976, Domen and Lamperti⁸ (DL) published the results of a detailed series of measurements using electron beams with energies from 15 to 50 MeV. They measured the response of a graphite calorimeter compared to a graphite ionization chamber for a wide range of depths in a graphite phantom. Ten years later, Svensson and Brahme⁹ extracted values of W_{air} from the DL data and found, surprisingly, a significant 2% variation as a function of electron energy (with the higher-energy results in reasonable agreement with the accepted value for ^{60}Co γ -rays). Since to our knowledge no physical effect can explain this anomalous

trend, we suppose that some perturbation effects that could not easily be estimated at the time may have been overlooked in the analysis. Or, as suggested back then, that the effect might be due to inaccurate stopping power values.

Given the benefit of a W_{air} value extracted from high energy data, we are prompted to re-examine the DL experiment in detail, using up-to-date stopping powers and the full breadth of modern Monte Carlo (MC) simulation. Our hypothesis at the outset is that more reliable calculations of the correction factors involved in the original measurement, by redressing the anomaly reported previously, could lead to a more precise and robust value for W_{air} . Unfortunately, this turns out not to be the case. The anomaly persists and forestalls any tightening of the uncertainty on W_{air} , although the range of extracted values overlaps with the accepted one.

Of note, DL also reported measurements for depths well beyond the electron practical range in graphite, i.e., where energy deposition relates to secondary bremsstrahlung photons rather than primary electrons. Analysis of this photon regime data yields W_{air} values which also compare favorably with recent values obtained using x-ray beams produced by clinical linacs.¹⁰

2 Theory

By definition, W_{air} is the ratio between the energy deposited and the number of ion pairs created, in a given air volume. It can be expressed in terms of absorbed dose to air, D_{air} , the ionized charge per unit mass of air, J_{air} , and the elementary charge, e , as follows:

$$W_{\text{air}} \equiv \frac{D_{\text{air}}}{J_{\text{air}}/e}. \quad (1)$$

Since it is not practical to measure energy deposition in air, it is measured instead in a surrogate dense media suitable for calorimetry, graphite being a prevailing choice. In terms of dose to graphite, D_{g} , we rewrite Eq. 1 identically as

$$W_{\text{air}} = \frac{D_{\text{g}}}{J_{\text{air}}/e} \left(\frac{D_{\text{air}}}{D_{\text{g}}} \right). \quad (2)$$

The first ratio on the right hand side is precisely the quantity R_{g} reported by DL (they report $D_{\text{g}}/J_{\text{air}}$ in units of J/C, so it is numerically equal to $D_{\text{g}}/(J_{\text{air}}/e)$ expressed in eV per ion pair).

The second, dimensionless ratio $D_{\text{air}}/D_{\text{g}}$ is an air-to-graphite dose correction factor, which must be evaluated to recover W_{air} . In the past this factor was estimated based on the ratio of the restricted, spectrum-averaged, electronic stopping power of air and graphite; indeed this is the dominant contribution. Nowadays, however, such correction factors are best calculated with MC, with the added benefit of taking into account other small perturbation effects that may have been overlooked by DL or Svensson and Brahme.

The ICRU Report 31² defines both a differential and integral form of the *mean energy expended in a gas per ion pair formed*. The differential quantity, w , relates to ions produced when a charged particle with kinetic energy, T , loses a small amount of energy, dT , while W relates to all ions produced when the particle has lost all of its energy. The two are related by

$$W(T) = T \int_I^T \frac{d\epsilon}{w(\epsilon)}, \quad (3)$$

where I is the lowest ionization potential of the absorber. Waibel and Grosswendt¹¹ have discussed the relationship between w_{air} and W_{air} for electrons with energies below about 5 keV. As the electron energy increases beyond 30 eV, both quantities decrease rapidly and become approximately constant at higher energy. The energy variation of w_{air} at low energies does not make an important contribution to the integral for MeV electrons. Thus, if w_{air} is assumed constant in Eq. 3, then W_{air} is equal to w_{air} . For this reason, in what follows, we will refer only to W_{air} even though the quantity being discussed may seem at times closer to the definition of w_{air} . Of course, finding that W_{air} varies with electron energy would imply the possibility that w_{air} is energy dependent for high-energy electrons as well.

3 Materials and Methods

We begin with a brief summary of the apparatus used by DL, reviewing how it was used, how the measurements were carried out and how the results were reported. We then describe our EGSnrc MC model of the key components of the DL setup which allows us to calculate effects that could not easily be estimated in 1976, or to confirm corrections that could only be estimated at the time.

3.1 Domen-Lamperti apparatus

The original motivation of DL was not to extract the value of W_{air} , but to establish a transfer standard. Calorimetry could not be used for routine dosimetry in electron beams, however they recognized that “With knowledge of the quotient of absorbed dose by specific charge [...] ionization-chamber measurements can be converted to absorbed-dose determination.” The main output of their work is an extensive data set of the quotient, in graphite, of the absorbed dose divided by charge per unit mass of air. They call “specific charge” the charge per unit mass of air, and we denote it by J_{air} . Thus, they tabulated the ratio $R_g \equiv D_g/J_{\text{air}}$, with D_g the absorbed dose in graphite.

A graphite calorimeter and a parallel-plate ionization chamber, depicted in Figure 1a, were mounted on a rail system that permitted either to be accurately positioned in front of an incident electron beam. A series of cylindrical graphite absorbers of different thicknesses were mounted on a large wheel in front of the detector, thus allowing the measuring depth in graphite to be varied. DL point out that the accelerator beam current was adjusted to maintain approximately the same dose rate across all measurements.

The graphite calorimeter has been described in detail in other papers^{12,13} and its behavior is well understood. The graphite ionization chamber, on the other hand, was built specifically for this experiment. It is a parallel-plate chamber with a well-defined and accurately measured collecting volume and a large guard ring. The collecting volume of the chamber was designed to be the same size as that of the calorimeter core. Figure 1a indicates that the centers of the core and the collecting volume were positioned at the same distance from the scattering foils during the measurements.

The electron beams were generated by the high energy electron linac^{14,15} installed at the NBS (now NIST). The pencil beam impinged on a scattering foil to produce an approximation to a broad, parallel beam at the measurement distance, which was typically 175 cm. To estimate the effect of the scattering foil, DL carried out a series of measurements of R_g for different foil thicknesses and extrapolated to zero to predict the value of R_g with no added foil. They also obtained R_g for several distances from 75 cm to 225 cm and with the measuring point offset from the central axis by up to 6 cm. From these ancillary measurements, they concluded that their data for R_g holds for a broad, parallel beam of monoenergetic electrons.

FIGURE 1 a) Original diagram of the ionization chamber and graphite calorimeter used by Domen and Lamperti to measure the ratio between the dose absorbed by the graphite calorimeter (bottom) and the specific charge collected by the ionization chamber (top). Reproduced with permission. b) EGSnrc model of the detectors, presented in the same fashion, captured from the EGSnrc geometry viewer. Graphite is shown in gray, air in green, plastic in yellow and vacuum in black; highlighted in red in both detectors is the $20 \text{ mm} \times 2.75 \text{ mm}$ dose scoring volume. In the simulation the gap between the absorber and the detector is vacuum, instead of air. The detector portion of the geometry shown here is further inscribed in a $40 \text{ cm} \times 30 \text{ cm}$ cylindrical graphite phantom (see Figure 2). As in the experiment, the simulations are run with *either* the ionization chamber or the calorimeter behind the absorber, not both at the same time.

FIGURE 2 MC simulation snapshots for a beam of 50 MeV electrons incident on the ionization chamber model, at depths in graphite of a) 0.9 g/cm² (no absorber); b) 6.37 g/cm²; and c) 21.35 g/cm² (at the limit of the electron regime). The graphite phantom and absorbers are rendered translucent and contoured in white for clarity. Note that only half of the 30 cm thick phantom is visible in these images. Particle tracks are shown for 1000 individual showers, with electrons in red, photons in yellow and positrons in blue. Every simulation is repeated with the graphite calorimeter model as well.

Although R_g is independent of air temperature and pressure, it does depend on humidity. At the time when DL carried out their work there was some doubt over the appropriate humidity correction for ionization chamber measurements, so DL applied no correction but added a corresponding uncertainty of 0.3 %. The humidity correction is now well established,^{2,16} hence we correct the DL data by multiplying J_{air} by 0.997.

3.2 Monte Carlo simulations

We use the EGSnrc software¹⁷ to model the DL ionization chamber and graphite calorimeter in detail, as shown in Figure 1b. With the `egs_chamber`¹⁸ application we calculate the dose ratio D_{air}/D_g for broad (20 cm wide), plane-parallel, monoenergetic beams of electrons, allegedly the conditions corresponding to the R_g ratio tabulated by DL. See Figure 2 for sample simulation pictures. According to Eq. 2, multiplying R_g by this MC calculated dose ratio yields the value of W_{air} .

In all simulations electrons and photons are tracked down to a kinetic energy of 10 keV (then transport is stopped and the remaining energy is deposited locally). Standard density effect correction files distributed with EGSnrc are used for air, PMMA, and Mylar. For graphite, a custom density correction file is generated with the ESTAR program,¹⁹ for a 2.265 g/cm³ grain density⁷ and for a mean excitation energy $I_g = 81$ eV.²⁰ Typical options for high accuracy simulation are selected (see EGSnrc input file in Supplemental Material). Range-based Russian roulette and correlated sampling variance reduction techniques are also

employed to increase simulation efficiency.¹⁸ A statistical uncertainty below 0.02 % on the dose to the ionization chamber is sought, which is typically attained within 10^{11} histories. For more details refer to the `egs_chamber` input file provided as supplementary material to this article.

The analysis also relies on other EGSnrc applications: SPRRZnrc to calculate graphite-to-air stopping-power ratios and FLURZnrc to determine the mean electron energy as a function of depth. Finally, BEAMnrc is used to model the generation of the scattered beam from the primary NBS electron beam, to verify the DL extrapolation method to convert scattered beam measurements into broad beam data. Unfortunately, DL do not specify the primary electron beam characteristics of the NBS linac; we take it to be a narrow monoenergetic beam with a Gaussian profile ($\sigma = 0.5$ mm) and no angular spread, and check that results are insensitive to reasonable changes in these assumptions.

4 Results

4.1 Domen and Lamperti data for R_g

The original dose per specific charge results published by DL are reproduced in Table 1, and summarized graphically in Figure 3, showing two distinct regimes. At shallow depths, the absorbed dose is attributed mainly to primary electrons; we call this the *electron regime*. At depths beyond the practical electron range, absorbed dose relates to secondary bremsstrahlung photons; we call this the *photon regime*. The standard uncertainties on the DL data range in size from 0.01 % to 0.55 %, with an average value of 0.15 %.

Near the end of the practical range of primary electrons, the electron spectrum changes rapidly as electrons produced from secondary bremsstrahlung photons begin to dominate (consider Figure 2c). Hence the trend in R_g also changes drastically near this transition between the two regimes, and the DL extrapolation to infer broad parallel beam equivalence becomes problematic.⁸ For this reason we shall confine our analysis to depths in graphite well removed from this critical point. Specifically, in the electron regime we only consider depths less than 80 % of the practical electron range, while in the photon regime we consider depths where the DL broad beam correction is negligible (following Figure 4 of the DL paper).

FIGURE 3 Graph of the DL data from Table 1 (divided by 0.997 to account for humidity). Straight line segments are added between points as a guide. On each curve, we use solid symbols for points in the electron regime (towards the left), and open symbols for points in the photon regime (towards the right). Uncertainties are barely visible on this graph since they are typically smaller than the symbol size.

TABLE 1 Original data published in 1976 by Domen and Lamperti for the dose by specific charge quotient, as a function of beam energy and depth in graphite. The number following the $\pm$ sign in each case is the standard deviation of the mean *in percent*, followed in parentheses by the number of measurements minus one (degrees of freedom). All data must be divided by 0.997 to account for humidity. The six omitted points are missing in the original table. Reproduced with permission.

Depth (g/cm ²)	Absorbed dose/specific charge in joules/coulomb					
	15 MeV	20 MeV	25 MeV	30 MeV	40 MeV	50 MeV
0.90	29.08 $\pm$ 0.01(1)	28.38 $\pm$ 0.04(8)	27.87 $\pm$ 0.04(1)	27.59 $\pm$ 0.06(18)	27.10 $\pm$ 0.08(8)	26.57 $\pm$ 0.49(1)
1.91	29.67 $\pm$ 0.02(1)	28.80 $\pm$ 0.06(1)	28.29 $\pm$ 0.24(1)			
2.88	30.13 $\pm$ 0.13(1)	29.14 $\pm$ 0.08 (3)	28.46 $\pm$ 0.10(3)	28.06 $\pm$ 0.07(1)	27.45 $\pm$ 0.29(1)	27.12 $\pm$ 0.06(1)
3.89	30.72 $\pm$ 0.01(1)	29.59 $\pm$ 0.09(7)	28.80 $\pm$ 0.15(1)	28.31 $\pm$ 0.06(11)	27.66 $\pm$ 0.05(7)	27.29 $\pm$ 0.19(1)
4.92	31.15 $\pm$ 0.13(1)	30.06 $\pm$ 0.02(3)	29.17 $\pm$ 0.23(1)	28.56 $\pm$ 0.04(10)	27.95 $\pm$ 0.35(1)	
6.37	32.33 $\pm$ 0.10(3)	30.62 $\pm$ 0.15(9)	29.71 $\pm$ 0.11(3)	28.97 $\pm$ 0.04(9)	28.15 $\pm$ 0.02(9)	27.69 $\pm$ 0.16(1)
7.84	34.66 $\pm$ 0.38(13)	31.29 $\pm$ 0.22(6)	30.36 $\pm$ 0.29(1)	29.49 $\pm$ 0.05(10)	28.53 $\pm$ 0.38(1)	27.92 $\pm$ 0.17(1)
10.83	32.73 $\pm$ 0.24(3)	33.64 $\pm$ 0.33(11)	31.72 $\pm$ 0.04(1)	30.44 $\pm$ 0.14(9)		
13.41	32.89 $\pm$ 0.55(3)	32.54 $\pm$ 0.19(3)	32.65 $\pm$ 0.38(11)	31.59 $\pm$ 0.09(29)	29.87 $\pm$ 0.08(1)	28.91 $\pm$ 0.08(13)
16.85	32.93 $\pm$ 0.01(1)	32.49 $\pm$ 0.10(3)	32.43 $\pm$ 0.17(1)	32.91 $\pm$ 0.21(13)	30.97 $\pm$ 0.15(1)	29.84 $\pm$ 0.31(1)
21.35	32.78 $\pm$ 0.09(2)	32.52 $\pm$ 0.18(5)	32.45 $\pm$ 0.10(1)	32.50 $\pm$ 0.22(9)	32.16 $\pm$ 0.27(3)	30.98 $\pm$ 0.27(1)
26.80	32.25 $\pm$ 0.06(3)	32.85 $\pm$ 0.07(4)	32.54 $\pm$ 0.27(6)	32.38 $\pm$ 0.12(7)	32.02 $\pm$ 0.07(14)	32.23 $\pm$ 0.09(10)
33.37	32.23 $\pm$ 0.21(3)	32.78 $\pm$ 0.16(5)	32.56 $\pm$ 0.13(8)	32.26 $\pm$ 0.25(8)	32.05 $\pm$ 0.07(5)	31.87 $\pm$ 0.10(7)
42.54	32.37 $\pm$ 0.18(3)	32.71 $\pm$ 0.14(13)	32.56 $\pm$ 0.26(8)	32.06 $\pm$ 0.09(12)	31.90 $\pm$ 0.07(7)	31.56 $\pm$ 0.09(9)
50.91	32.46 $\pm$ 0.51(3)	32.72 $\pm$ 0.21(9)	32.39 $\pm$ 0.14(8)	32.02 $\pm$ 0.11(17)	31.76 $\pm$ 0.16(8)	31.50 $\pm$ 0.09(11)

4.2 Monte Carlo data for $D_{\text{air}}/D_{\text{g}}$

For completeness, Table 2 tallies the raw simulation results for the MC calculated $D_{\text{air}}/D_{\text{g}}$ dose ratio, collected directly from simulation output files, with no post-processing. Simulations are carried out to a precision of 0.02 % in the electron regime, and to 0.05 % in the photon regime, on par or better than the experimental uncertainty for most data points, in order to curb MC statistical noise in the W_{air} analysis.

4.3 Extracted W_{air} values

The central results of this paper are the values of W_{air} listed in Table 3, obtained by multiplying the experimental DL data (corrected for humidity) and the MC derived values for $D_{\text{air}}/D_{\text{g}}$, following Eq. 2. This data is portrayed graphically in Figure 4. For the sake of clarity, the electron regime data is isolated in the left pane of the graph, while the photon regime data is shown in the right pane (on a slightly compressed, and partly overlapping horizontal scale). The currently accepted value $W_{\text{air}} = (33.97 \pm 0.11)$ eV is highlighted in the middle of the vertical axis.

FIGURE 4 Graph of the extracted W_{air} data from Table 3, as a function of depth in graphite, for each incident beam energy, in a) the electron regime; and b) the photon regime. Each curve is labeled by incident beam energy, and straight line segments between points serve as a guide. Statistical uncertainties are included as vertical bars. The horizontal black line and the shaded vertical range denote the accepted value of W_{air} and its standard uncertainty: (33.97 ± 0.11) eV.

TABLE 2 MC calculation results for the ratio between the dose to the ionization chamber cavity air and to the graphite calorimeter, using an EGSnrc model of the DL apparatus. The statistical uncertainty on the last two digits is given in parentheses. Values typeset in gray in each column divide the electron regime values (top) from the photon regime ones (bottom).

Depth (g/cm ²)	$D_{\text{air}}/D_{\text{g}}$					
	15 MeV	20 MeV	25 MeV	30 MeV	40 MeV	50 MeV
0.90	1.16808 (20)	1.19129 (21)	1.20994 (21)	1.22546 (22)	1.24601 (21)	1.25814 (22)
1.91	1.15132 (21)	1.17735 (22)	1.19642 (22)	1.21236 (22)	1.23535 (23)	1.24815 (23)
2.88	1.13526 (22)	1.16422 (22)	1.18558 (22)	1.20266 (22)	1.22692 (22)	1.24093 (22)
3.89	1.11841 (23)	1.15088 (22)	1.17476 (22)	1.19274 (25)	1.21924 (23)	1.23448 (23)
4.92	1.10125 (23)	1.13637 (23)	1.16272 (23)	1.18225 (23)	1.21059 (23)	1.22762 (23)
6.37	1.07336 (23)	1.11580 (23)	1.14591 (23)	1.16801 (23)	1.19920 (23)	1.21848 (23)
7.84	1.03029 (47)	1.09392 (24)	1.12710 (23)	1.15237 (23)	1.18678 (24)	1.20906 (24)
10.83	1.02964 (57)	1.02877 (49)	1.08691 (23)	1.11796 (24)	1.16074 (56)	1.18903 (24)
13.41	1.02668 (61)	1.03342 (55)	1.04057 (48)	1.08741 (23)	1.13749 (24)	1.16990 (24)
16.85	1.02543 (59)	1.03153 (63)	1.03819 (55)	1.03221 (51)	1.10480 (23)	1.14365 (24)
21.35	1.02413 (58)	1.03099 (61)	1.03716 (63)	1.04474 (58)	1.05581 (49)	1.10684 (29)
26.80	1.02387 (63)	1.03203 (58)	1.03893 (61)	1.04374 (63)	1.05526 (57)	1.06142 (50)
33.37	1.02483 (70)	1.03415 (57)	1.04220 (59)	1.04809 (62)	1.05773 (65)	1.06564 (58)
42.54	1.02713 (84)	1.03669 (63)	1.04383 (58)	1.05099 (59)	1.06087 (64)	1.06854 (67)
50.91	1.03089 (104)	1.03940 (70)	1.04838 (63)	1.05467 (59)	1.06536 (62)	1.07367 (65)

4.3.1 Electron regime

The electron regime data in Figure 4a reveals a dependence on the incident beam energy and depth in graphite. *This*, precisely, is the anomaly, since the value of W_{air} is expected to be constant in this energy range. Since DL used both the beam energy and the depth in graphite to modulate the energy of the electrons reaching the ion chamber cavity (or calorimeter core), the results are best interpreted in terms of that single parameter. Using the EGSnrc application FLURZnrc, the mean kinetic energy of the electrons at the point of measurement is calculated (data not shown), and in Figure 5 the W_{air} electron regime data is replotted as a function of this energy. The ordinates of these data points are the same as in Figure 4. Thus in terms of electron energy, all points cluster around a single trend line, exhibiting a 3% increase as the energy of the electrons decreases from about 30 MeV to 2 MeV. The rightmost data point is deemed an outlier.

TABLE 3 Values of W_{air} extracted from the DL data and MC calculations of air-to-graphite dose ratios. This table is obtained by multiplying the corresponding numbers in Table 1 and Table 2, and dividing by 0.997 to account for the humidity correction. The uncertainty on the last two digits is given in parentheses. Values typeset in gray in each column divide the electron regime values (top) from the photon regime ones (bottom).

Depth (g/cm ²)	W_{air} (eV)					
	15 MeV	20 MeV	25 MeV	30 MeV	40 MeV	50 MeV
0.90	34.070 (07)	33.911 (15)	33.822 (15)	33.912 (21)	33.868 (28)	33.529 (164)
1.91	34.262 (09)	34.010 (21)	33.949 (82)			
2.88	34.308 (45)	34.027 (28)	33.843 (34)	33.848 (24)	33.780 (98)	33.755 (21)
3.89	34.461 (08)	34.157 (31)	33.935 (51)	33.868 (22)	33.826 (18)	33.790 (65)
4.92	34.407 (45)	34.262 (10)	34.019 (79)	33.867 (15)	33.938 (119)	
6.37	34.806 (36)	34.269 (52)	34.147 (38)	33.939 (15)	33.859 (09)	33.841 (55)
7.84	35.817 (137)	34.332 (76)	34.322 (100)	34.086 (18)	33.961 (129)	33.859 (58)
10.83	33.802 (83)	34.712 (116)	34.581 (16)	34.133 (48)		
13.41	33.869 (187)	33.729 (67)	34.077 (130)	34.455 (32)	34.079 (28)	33.924 (28)
16.85	33.869 (20)	33.615 (39)	33.770 (60)	34.072 (74)	34.319 (52)	34.229 (106)
21.35	33.672 (36)	33.629 (64)	33.757 (39)	34.056 (77)	34.057 (93)	34.393 (93)
26.80	33.119 (28)	34.004 (31)	33.909 (94)	33.898 (46)	33.891 (30)	34.313 (35)
33.37	33.130 (73)	34.001 (58)	34.036 (48)	33.913 (87)	34.002 (32)	34.064 (39)
42.54	33.348 (66)	34.012 (52)	34.089 (91)	33.796 (36)	33.944 (31)	33.825 (37)
50.91	33.563 (174)	34.112 (75)	34.059 (52)	33.872 (42)	33.938 (58)	33.922 (37)

For reference, the trend line from the previous analysis by Svensson and Brahme⁹ is included as a dashed line in Figure 5. Hence MC calculations soften the reported anomalous trend slightly, by up to about 0.5 %, mostly on account of more accurate stopping powers, and in a smaller measure on account of accurate detector perturbation corrections. However, these improvements cannot in the end redress the anomaly.

4.3.2 Photon regime

At depths well beyond the range of the primary electrons, the absorbed dose relates to electrons set in motion by secondary bremsstrahlung photons. In this regime, R_g varies slowly with depth and is only weakly dependent on the energy of the incident electrons (see Figure 3). DL showed that the scattering foil correction was negligible in this case, however

FIGURE 5 Extracted W_{air} data as a function of the mean kinetic energy of the electrons at the point of measurement, in the electron regime. For reference, data sets for different incident beam energy are represented by different symbols, as labeled. The horizontal black line and the shaded vertical range denote the accepted W_{air} value and its standard uncertainty. A solid trend curve is added as a guide (disregarding the uncertain, rightmost data point). The dashed line is the trend curve obtained earlier by Svensson and Brahme.⁹

the detector perturbation effects are somewhat larger (data not shown). The photon region W_{air} results are shown graphically in Figure 4b.

It is immediately apparent that the results for 15 MeV are not consistent with those for other beams. This is due to irregular experimental data, as seen already in Figure 3, where the 15 MeV data would be expected to be the top curve towards higher depths. But instead it crosses the other data sets and exhibits a broad minimum near 30 g/cm². On that account—and because MC calculated $D_{\text{air}}/D_{\text{g}}$ values do not mirror any such irregular trend—the 15 MeV data in the photon regime is deemed flawed. By contrast, no such argument holds in the electron regime, where the 15 MeV data follows a regular progression in R_{g} compared with other beams, as seen on the left side of Figure 3. But this certainly does cast a doubt on the reliability of the experimental 15 MeV data set, overall.

Without the 15 MeV data, the weighted average of the photon regime data yields $W_{\text{air}} = (33.908 \pm 0.002)$ eV, which is statistically within range of the accepted value; although since $\chi^2 \approx 12$ per degree of freedom, fitting to a constant is not rigorously consistent here. Including the 15 MeV data would reduce this weighted average down to (33.820 ± 0.002) eV, which is not consistent with the accepted value. If we further restrict the average to graphite depths above 25 g/cm², we find $W_{\text{air}} = (33.946 \pm 0.002)$ eV, in closer agreement with the accepted value, as can already be inferred from Figure 4b.

5 Discussion

For several years NBS (now NIST) operated an electron accelerator²¹ that could produce electron beams with energies from as low as 10 MeV to more than 100 MeV. During the same period DL had perfected the design of a graphite calorimeter that could be used to measure, with excellent accuracy, the absorbed dose to graphite.¹² With the construction of a plane-parallel graphite ionization chamber having an air cavity with a well-known volume they were able to carry out an extensive set of measurements comparing the absorbed dose to graphite to the specific charge produced in the air cavity. We have used their measured data together with MC simulation to extract new values of W_{air} for depths less than the range of the primary electrons (electron regime) and for depths beyond the range of primary electrons (photon regime).

The W_{air} values extracted from the photon regime data (excluding the 15 MeV measurements) are in statistical agreement with the currently recommended value $W_{\text{air}} = (33.97 \pm 0.11)$ eV. On the other hand, in the electron regime, and using the best available stopping powers and applying all known corrections, W_{air} still shows an unexpected energy dependence, as first noted by Svensson and Brahme.⁹ This anomaly lies well outside the uncertainties estimated by DL, hence it begs the question: *what could have possibly gone wrong?* We devote the rest of this discussion to the effects we have considered in our attempts to answer this question.

5.1 Extrapolation and energy loss corrections

DL used lead scattering foils to produce a divergent electron beam that was approximately uniform in cross section over several centimeters at the position of the detectors. These foils degraded the electron energy and led to the production of bremsstrahlung. To account for these effects, each set of measurements was repeated for different scattering foil thicknesses and extrapolated linearly to zero foil thickness (see Figure 3 in the DL paper⁸). It was also necessary to account for the energy loss in the linac aluminum exit window (mass thickness 0.1 g/cm²), and for the energy loss in the air column between the scattering foil and the detector. Having made all these corrections, DL claim that their corrected values for R_g in Table 1 apply to a broad, parallel beam of monoenergetic electrons with the energy shown at the top of the table, for a depth in graphite given by the mass thickness in leftmost column.

This claim ought to be scrutinized, because linear extrapolation can be misleading—one famous example being the determination of the ionization chamber wall effect for air kerma standards²²—and energy loss calculations based on stopping power completely ignore spectral dispersion and thus yield a poor estimate of actual scattered electron energies.

Unfortunately, the original paper does not report the raw measurement data, only the final, corrected R_g values. Therefore we can only gauge the validity of the DL approach indirectly, from the error incurred when following the same procedure to correct the calculated D_g/D_{air} ratio (as a stand-in for R_g). To this end, additional MC simulations were carried out using the BEAMnrc application to model the entire experimental setup including the aluminum exit window, the lead foil, and the air column. The dose ratio as a function of foil thickness was determined, using the same thicknesses as in the original measurements (0.013, 0.025,

0.089 and 0.14 cm). This ratio was then extrapolated to zero foil thickness, and corrected for energy loss according to total stopping powers. Any difference between these “corrected” values and the “exact” broad beam MC results would then suggest a flaw in the DL correction procedure.

A representative subset of the MC results for the scattering foil extrapolation are shown in Figure 6. The ratio D_g/D_{air} was extrapolated to zero foil thickness, as marked by crosses, using a weighted linear fit. These values have to be corrected further to account for energy loss and, finally, compared with the broad beam results marked by solid symbols in the figure. For this last correction, DL relied on electron stopping power data to estimate the electron energy loss through the aluminum exit window and through air, and interpolated their measured values of R_g to revert this loss. They did not report their calculated energy loss for each beam energy, only average values of 0.25 MeV in aluminum and 0.5 MeV in the air column. After interpolation their corresponding R_g corrections were 0–0.3% due to aluminum and 0–0.6% due to air; but again they did not quote individual values.

In Table 4 we show the energy loss we calculated from the total stopping power for aluminum and air, for each incident beam energy. Note that the small energy loss in the aluminum is not taken into account before evaluating the air stopping power (doing so would reduce the energy losses by about 0.002 MeV, which proves negligible in this context). The average loss in aluminum is about 0.27 MeV, similar to the 0.25 MeV figure quoted by DL. The average loss in air is about 0.60 MeV, which is higher than the 0.5 MeV average quoted by DL. However if we repeat our calculation with source-detector distances ranging from 75 cm to 225 cm, as they did, we find an average energy loss in air of about 0.51 MeV. By interpolating the Monte Carlo data from Table 2 as a function of energy, we find energy loss corrections on D_g/D_{air} ranging between 0.1% and 0.9%, also in agreement with the overall 0–0.9% range reported in the original paper. Hence we deem our energy loss correction to be consistent with the one applied by DL.

Finally, we compare our extrapolated, energy loss corrected values of D_g/D_{air} against the “exact” values obtained from broad, parallel beam simulations. Figure 7 shows the relative error incurred in D_g/D_{air} as a result of the correction, for a representative set of energies and depths in graphite. This figure shows, for example, that for a 50 MeV beam and a depth of 21.35 g/cm², the correction overestimates the true dose ratio by nearly 0.6%. We find that in all cases the correction-induced error lies in the 0–0.6% range. In particular, the

FIGURE 6 Monte Carlo simulation to convert diverging beam measurements to values relevant to broad, parallel beams, following the DL lead foil extrapolation technique. In this data subset, each curve is labeled with the incident beam energy in MeV and the depth in graphite in g/cm². The bottom three sets correspond to the minimum depth, 0.9 g/cm², while the three top sets correspond to the maximum depth in the electron regime (which depends on the energy). Open symbols represent calculation using a realistic model of the experimental setup, and solid lines correspond to weighted linear fits. The extrapolated dose ratio at zero foil thickness is marked by a cross, and the parallel beam simulation result is denoted by a solid symbol.

TABLE 4 Energy loss calculated from total stopping powers for electrons in aluminum and air, for each incident beam energy, to three significant figures. Stopping-powers for both aluminum and air are evaluated at the nominal beam energy.

Material	Thickness (cm)	Energy loss estimated from total stopping powers (MeV)					
		15 MeV	20 MeV	25 MeV	30 MeV	40 MeV	50 MeV
Aluminum	0.037	0.213	0.234	0.254	0.274	0.315	0.355
Air	175	0.497	0.535	0.571	0.605	0.668	0.728
Total		0.711	0.769	0.825	0.879	0.983	1.08

correction is accurate to better than 0.1 % for the 15 MeV beam (although the correction itself can approach 1 % for this beam).

Figure 7 graph implies that the DL values of R_g are not overestimated by more than about 0.6 % on the sole account of the correction procedure. Hence we are led to conclude that inaccuracies in the extrapolation and energy loss correction method used by DL cannot account for the anomalous trend in the extracted W_{air} values; especially not for the 15 MeV data set.

5.2 Electron stopping powers

It was pointed out following Eq. 2 that the dose ratio D_{air}/D_g is closely related to the ratio of the electronic stopping powers of graphite and air, which are part of the physical data supplied to the Monte Carlo code in order to extract W_{air} . The stopping power data, especially for graphite, has been revised in the past few years, culminating in new recommendations in ICRU Report 90.²⁰ The results presented here are based on the new data which specify 85.7(12) eV and 81.0(18) eV for the mean excitation energies for air and graphite, respectively. The ICRU also recommends that the crystalline density be used when evaluating the density effect for graphite, rather than the bulk density. For the range of electron energies relevant to this work, the change to the graphite stopping power compared to the values recommended by the previous ICRU Report 37²³ ranges from about 0.6 to 1.2 %. The data for air have remained unchanged.

FIGURE 7 Relative error incurred in D_g/D_{air} as a result of applying the lead foil extrapolation and energy loss correction, as opposed to using a true broad, parallel beam. The error bars denote the statistical uncertainties of the broad beam Monte Carlo simulation only (the uncertainties on the extrapolated value and the energy loss correction are comparatively small).

ICRU Report 90²⁰ shows how the uncertainty of the mean excitation energy contributes to the uncertainty of the electronic stopping power. The effect is energy dependent so we will consider the energy range from 1 to 50 MeV as representative of the data required for this work. Adding in quadrature the contributions of graphite and air leads to 0.20 % at 1 MeV, decreasing to 0.05 % by 50 MeV. These contributions are small compared to the overall uncertainty of 0.5 to 1 % that ICRU Report 90 suggests.

The stopping power measurements by MacPherson⁷ in the energy range from 5 to 30 MeV have an uncertainty of about 0.3 % for graphite. The measured and calculated stopping powers are in agreement if the crystalline density is used when calculating the density effect. There are no measured data for air but MacPherson reported satisfactory agreement between measurements and calculations for a wide range of materials. Thus, it seems reasonable to assume that the uncertainty on the calculated electronic stopping power for air is no worse than 0.3 %. Then the uncertainty of the graphite to air stopping power ratio can be estimated to be about 0.4 %. Hence we conclude that the anomalous W_{air} trend in the electron regime cannot be explained by uncertainties in stopping power data.

5.3 Calorimetry

DL point out that they used a dose rate that was high enough to permit short runs (less than 100 seconds) and the accelerator beam current was adjusted to achieve approximately the same dose rate at all energies and depths. They restored thermal equilibrium after each run by introducing air into the calorimeter vacuum gaps for a few minutes. We considered the possibility that thermal isolation was not restored completely owing to the difficulty of pumping residual air from the small vacuum gaps. We carried out thermal modelling for different values of residual pressure, but the results (not shown) indicate that the corresponding heat loss correction, for short runs, would not be substantial. Furthermore, DL claim the measured heat loss correction was less than 0.03 %. We cannot identify any other issues related to calorimetry that might lead to systematic effects.

5.4 Ionization chamber

To our knowledge, the ionization chamber was not used for any other work. DL state that measurements were done at both polarities and that recombination corrections were about 0.1 %. There is some uncertainty regarding the insulator for the high voltage electrode of the chamber which is simply described as a “plastic ring” (see Figure 1). We used Monte Carlo calculations to test how different plastics might affect the ionization chamber response. For typical plastics, the effect on the response was within 0.1 %. We also tested the sensitivity of the calculated D_{air}/D_g with respect to the material composition and the thickness of the epoxy resin that supports the collecting electrode (see Figure 1). We found at most a 0.2 % effect in extreme cases where epoxy is replaced by graphite outright, or when the radius of the epoxy ring is varied by 1 mm. We cannot identify any other issues that might lead to systematic effects.

5.5 Graphite absorbers

Experimentally, the depth in graphite was modulated with combinations of graphite discs positioned in front of the ionization chamber or calorimeter. Figure 5 shows that the anomalous behavior sets in at a mean electron energy of about 15 MeV, regardless of the incident beam energy. This suggests that perhaps the actual graphite mass thickness was non-uniform and greater near the central axis (in front of the detectors). Then R_g would have to be corrected down, and more so for larger depths, which in turn would flatten the W_{air} anomaly. Unfortunately, it proved impossible to locate the original absorbers to confirm their densities. However, Steve Domen kindly perused his old laboratory notebooks to find the raw density measurement data. He reported an average density value and standard deviation of (1.665 ± 0.007) g/cm³ for the set of 9 graphite discs used in the experiment. This is admittedly a small standard deviation in light of data he collected for a second set of 11 graphite discs manufactured at the same time: (1.73 ± 0.08) g/cm³. Although the mass thicknesses listed in Table 1 were determined for each disc independently, and set accordingly in the simulations, the large standard deviation in the second set of discs casts a small doubt on the intrinsic density variations within each disc. However, modelling reveals (data not shown) that even for a graphite density approaching 1.9 g/cm³—anything higher deemed unlikely for manufactured graphite—the W_{air} variations in Figure 4a, though reduced, are not com-

pletely resolved. More importantly, the curves for different beam energies move down more or less in unison when the absorber graphite density increases, so overall the problem stands. Finally, at least one reference suggests that the density of a graphite rod may be minimum rather than maximum near the central axis.²⁴ For all these reasons, we conclude that density variations in the graphite absorbers cannot account for the W_{air} anomaly.

5.6 Detector graphite mass thickness

The DL experiment is quite sensitive, it turns out, to the 0.90 g/cm^3 graphite mass thickness in front of the ionization chamber cavity or calorimeter core. Any offset in this intrinsic mass thickness between the two detectors would affect the calculated $D_{\text{air}}/D_{\text{g}}$ ratio, and thus W_{air} . In the 1976 paper⁸ this mass thickness is expressed with either 2 and 3 significant digits (0.90 g/cm^3 and 900 mg/cm^3), but no uncertainty is quoted explicitly. DL state¹² that the entire calorimeter assembly was machined from the same block of 99.9% pure graphite of density $\rho = 1.70 \text{ g/cm}^3$, yet the core disc dimensions (20 mm in diameter and 2.75 mm thick) and mass (1.434 g) imply a density of 1.66 g/cm^3 , i.e., about 2.5% lower. Moreover, the original calorimeter blueprints quote the graphite density simply as $\rho \sim 1.7 \text{ g/cm}^3$, and the machining tolerances as roughly 0.1 mm (0.005 inches) for each of the 3 graphite caps enclosing the core. The front plate of the ionization chamber was machined as a single graphite plate, but from a different graphite block. As mentioned in Section 5.5, density variations between blocks or even within a given block are a real concern. Finally, it is unclear how the 0.013 cm Mylar window in the calorimeter was accounted for (see Figure 1; we assumed it accounted for 0.018 g/cm^2). All these considerations lead us to contemplate the impact of a few percent mismatch in the nominal 0.90 g/cm^3 intrinsic mass thickness between the two detectors.

Let us assume for the sake of argument that the 0.90 g/cm^3 figure is accurate for the ionization chamber, but that in reality it was 5% lower in the calorimeter. It is not necessary to run additional simulations to investigate this point. Indeed, precise Monte Carlo calculated dose distributions in graphite for the various incident beam energies (data not shown) allow us to predict how D_{g} (and thus the $D_{\text{air}}/D_{\text{g}}$ ratio) shifts with mass thickness. This is shown in Figure 8a. For each beam, at depths beyond the electron dose distribution maximum, W_{air} moves downward considerably (because the D_{g} gradient is negative and steep), hence

FIGURE 8 Possible adjustments to W_{air} in the electron regime, to account for a) an offset of -5% ($-0.045 \text{ g}/\text{cm}^2$) in the calorimeter intrinsic graphite density (dashed lines delineate the original data, and solid lines represent the adjusted values); and b) *additional* adjustments to the nominal incident beam energies, as labeled (lines between points are removed for the sake of clarity). Adjusted data in both cases are generated by interpolation of the original simulation data in terms of depth and energy. The horizontal black line and the shaded vertical range denote the accepted value of W_{air} and its standard uncertainty.

it is not robust against density variations. On the other hand, for shallower locations W_{air} moves up only slightly (because the D_g gradient is positive and small), and is comparatively robust. For reference, the electron dose maximum for 15, 20, 25, 30, 40, and 50 MeV beams are located approximately at 4.7, 6.1, 7.2, 7.7, 8.9 and 9.8 g/cm^2 , respectively. Hence, given some uncertainty on the graphite density, it would seem wise to exclude from the analysis points beyond the electron dose maximum (the points that moved down in Figure 8a).

5.7 Beam energy

DL provide very little information on the characteristics of the accelerator beam. They state that the rms fluctuation in beam energy was about 0.25 MeV but do not give any indication

as to how well the beam energy was known. There is some published literature on the NBS accelerator laboratory but we have not been able to identify which beam line was used for the DL work. In general, if the incident electron beam energies were different than the stated values, the anomalous trend could be reduced, almost eliminated. To illustrate this point, Figure 8b shows the individual beam energies that would be required, on top of the intrinsic mass thickness adjustment from panel (a), for each data set to average out to the accepted value for W_{air} . The 15 MeV beam requires the largest adjustment at -8% , the 30 MeV beam is fine as is, while the 50 MeV beam would need a 1% boost (the other beams requiring intermediate adjustments, as labeled in the figure). Again, these data are predicted from interpolation of $D_{\text{air}}/D_{\text{g}}$ as a function of energy, but are borne out perfectly by explicit simulations (data not shown), except for maximal graphite depths since the interpolations neglect the correlation between the two types of adjustments.

Experimentally, such beam energy offsets are conceivable: quoting from an (unrelated) earlier report on beam monitoring at the NBS linac: “energy measurements are good to about $\pm 5\%$ ”.²⁵ Moreover, because DL sought to maintain a constant dose rate as the depth was changed, they had to increase the electron current substantially as thicker absorbers were added. We could suppose that the beam energy tended to decrease as the current increased, which could explain the slight but persisting upward trend in Figure 8b; however we have no independent evidence to support this conjecture.

5.8 Beam geometry

The 15 MeV data in the photon regime is notably anomalous (see Figure 4b). The uncertainty remains small but the measured values deviate substantially from the expected behavior. The deviation is so large that it cannot be explained by any possible change in the beam energy. At 15 MeV in the photon regime the beam current will need to be perhaps three orders of magnitude larger than that required for the electron regime. We note from the DL setup (Figure 1) that the incident beam is not collimated so there will be a spray of electrons and photons irradiating nearby cables. Induced spurious cable currents might lead to effects that would not affect precision but would give rise to systematic offsets. The authors also do not comment on how beam steering was maintained or checked. It may be that beam alignment changed as the beam current was increased, but again this remains a conjecture.

6 Conclusion

We carried out Monte Carlo simulations of a 1976 experiment by Domen and Lamperti, in order to extract a value of W_{air} from electron beams with incident energies ranging from 15 to 50 MeV. Despite high accuracy calculations of the $D_{\text{air}}/D_{\text{g}}$ dose ratio, using a faithful model of the detectors, we are unable to resolve conclusively the anomalous dependence of W_{air} on energy in the electron regime, first noted by Svensson and Brahme in 1986. For electron energies below about 10 keV, W_{air} is known to show a strong dependence on electron energy. Although there is no fundamental reason why it need be so, W_{air} is generally assumed to be independent of electron energy when the energy is well above 10 keV. In principle, the data in Figure 5 could suggest that W_{air} in fact exhibits an energy dependence for electrons with energies from a few MeV to 15 MeV; strictly speaking, this possibility still cannot be excluded. However, the data do not join in a satisfactory way to the well-established results for ^{60}Co γ -rays and MV x-ray beams;^{10,20} hence the dependence is considered anomalous.

We investigated a number of possible reasons as to why the original experimental data might have been skewed. Our analysis shows that the following factors are unlikely to be significant in this regard: a) errors in extrapolations and correction procedures; b) uncertainties in electron stopping powers; c) bias in calorimetry or ionization chamber measurements; and d) the density of the graphite absorbers. By way of contrast, the results are found to be quite sensitive to the intrinsic graphite mass thickness of the detectors and to the incident beam energy. In fact, generous yet plausible variations of a few percent in these parameters could in and of themselves account for the reported W_{air} dependence on energy. At the very least, the accepted value $W_{\text{air}} = (33.97 \pm 0.11)$ eV certainly cannot be excluded by this experiment in the face of uncertainties in those parameters. The accepted value is also supported by the photon regime data (with the exclusion of the 15 MeV outlier data set, see Figure 4b).

Another insight afforded by the numerous simulations performed for this work is that data for higher energy electrons are remarkably insensitive to variations in materials, detector dimensions, and physical parameters. Hence the considerable value in pursuing W_{air} measurements in this range. We note that for such higher energy electrons, W_{air} is found to be systematically 0.2–0.3 % below the currently accepted value (see Figure 5, above 15 MeV).

Reliable values of W_{air} for high energy electrons would fill a gap in the data available for the absorbed dose protocols^{26,27} that form the basis of radiation therapy. One option would be to simply repeat the Domen and Lamperti measurements using a suitable electron beam. This work demonstrates that the measurement protocol is sound, but consideration should be given to using another material for the calorimeter and ionization chamber, such as aluminum or magnesium, to alleviate concerns surrounding the density of graphite. The value of W_{air} should be independent of the choice of phantom material and any differences from results obtained with graphite would help to identify systematic errors. The intrinsic mass density of the detectors and the beam energy should be determined most carefully, ideally with sub-percent precision. Nowadays, beams and detectors can be modeled in exquisite detail with Monte Carlo simulation, eliminating the need for empirical extrapolations and corrections.

Another approach would be that used by Barber²⁸ in 1955. In this case, an electron beam with a well-established beam current is allowed to pass through a gas-filled ionization chamber. The ionization chamber is constructed so that ions are collected over a known length thus establishing knowledge of the number of ions per unit length per incident electron. If the stopping power of the gas filling the ionization chamber is assumed known then a value for W_{air} can be extracted. The electron stopping powers and their associated uncertainties are better known than they were in 1955 and again, Monte Carlo simulations can be relied upon to calculate the energy lost by the electron beam.

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Although retired for many years, Steve Domen of NIST participated in many helpful exchanges. He consulted old notebooks to extract data on graphite density and he searched the NIST laboratories for the graphite absorbers described in the 1976 paper. Sam Penner of NIST, also retired, commented on the energy calibration of the NBS electron linac. We had several helpful discussions with Malcolm McEwen (NRC) and he has initiated a project to measure W_{air} using electron beams produced by the NRC linac. Many hours of computing time were required for the Monte Carlo calculations and we are grateful to the NRC Research Computing Support Group, and in particular Michel Proulx (retired) and André Charbonneau for maintaining our high performance computing equipment.

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