Polarity effects and apparent ion recombination in microionization chambers

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(Received 22 November 2015; revised 11 February 2016; accepted for publication 15 March 2016; published 5 April 2016; corrected 28 April 2016)

Purpose: Microchambers demonstrate anomalous voltage-dependent polarity effects. Existing polarity and ion recombination correction factors do not account for these effects. As a result, many commercial microchamber models do not meet the specification of a reference-class ionization chamber as defined by the American Association of Physicists in Medicine. The purpose of this investigation is to determine the cause of these voltage-dependent polarity effects.

Methods: A series of microchamber prototypes were produced to isolate the source of the voltage-dependent polarity effects. Parameters including ionization-chamber collecting-volume size, stem and cable irradiation, chamber assembly, contaminants, high-Z materials, and individual chamber components were investigated. Measurements were performed with electrodes coated with graphite to isolate electrode conductivity. Chamber response was measured as the potential bias of the guard electrode was altered with respect to the collecting electrode, through the integration of additional power supplies. Ionization chamber models were also simulated using 

Results: Investigations with microchamber prototypes demonstrated that the significant source of the voltage-dependent polarity effects was a potential difference between the guard and collecting electrodes of the chambers. The voltage-dependent polarity effects for each prototype were primarily isolated to either the guard or collecting electrode. Polarity effects were reduced by coating the isolated electrode with a conductive layer of graphite. Polarity effects were increased by introducing a potential difference between the electrodes. 

Simulations further demonstrated that for a given potential difference between electrodes, the collecting volume of the chamber changed as the applied voltage was altered, producing voltage-dependent polarity effects in the chamber response. Ionization chamber measurements and simulations demonstrated an inverse relationship between the chamber collecting volume size and the severity of voltage-dependent polarity effects on chamber response. The effect of a given potential difference on chamber polarity effects was roughly ten times greater for microchambers as compared to Farmer-type chambers. Stem and cable irradiations, chamber assembly, contaminants, and high-Z materials were not found to be a significant source of the voltage-dependent polarity effects.

Conclusions: A potential difference between the guard and collecting electrodes was found to be the primary source of the voltage-dependent polarity effects demonstrated by microchambers. For a given potential difference between electrodes, the relative change in the collecting volume is smaller for larger-volume chambers, illustrating why these polarity effects are not seen in larger-volume chambers with similar guard and collecting electrode designs. Thus, for small-volume chambers, it is necessary to reduce the potential difference between the guard and collecting electrodes in order to reduce polarity effects for reference dosimetry measurements. © 2016 American Association of Physicists in Medicine. [http://dx.doi.org/10.1118/1.4944872]

Key words: radiation dosimetry, metrology, calibration

1. INTRODUCTION

An increase in the delivery of small and nonstandard radiation fields has led to the development of small-volume ionization chambers (<0.02 cm³), commonly categorized as microchambers. Small-volume dosimeters can provide high spatial resolution in areas of steep dose gradients. The University of Wisconsin Accredited Dosimetry Calibration Laboratory (UWADCL) has experienced an increase in requests for the calibration of microchambers for low- and
medium-energy x-ray beams as well as the $^{60}$Co beam. This indicates that these chambers are being used for reference-dosimetry measurements in a wide range of therapy and lower-energy x-ray applications.

Unfortunately, microchambers exhibit anomalous polarity effects that vary with the magnitude of the applied voltage, referred to as voltage-dependent polarity effects, which are not demonstrated by larger-volume, reference-class ionization chambers. Several publications have highlighted the large polarity effects\(^1\)\(^-\)\(^4\) and an inverse proportionality between chamber response and applied voltage;\(^1\)\(^,\)\(^5\) however, little work has been done to determine the cause of these behaviors. Without an understanding of the processes that compete with the collection of the true radiation-induced gas ionization in microchambers, the reliability and applicability of these chambers is uncertain. As a result, the American Association of Physicists in Medicine (AAPM) TG-51 addendum\(^6\) only provides reference-class data for chambers with a collecting volume greater than 0.05 cm\(^3\).

The focus of this investigation is to understand the source of the anomalous voltage-dependent polarity effects demonstrated by microchambers. There are a multitude of causes of polarity effects in ionization chambers, and the literature exploring these effects has been summarized by Abdel-Rahman\ et\ al.\(^7\)\(^,\)\(^8\). In this work, a series of microchamber prototypes were assembled to isolate the source of the voltage-dependent polarity effects for small-volume chambers. The effects of ionization-chamber collecting-volume size, stem and cable irradiation, chamber assembly, contaminants, high-Z materials, and individual chamber components were investigated. In addition, the presence and effect of a potential difference in the bias of the chamber electrodes were investigated. The goal of this work is to identify the source of the anomalous polarity effect demonstrated by microchambers so that the effects may either be corrected for in dose calculations or eliminated through optimized ionization chamber design.

## 2. METHODS AND MATERIALS

In order to characterize and isolate the source of microchamber polarity effects, several chamber prototypes were developed for this investigation. The dimensions and materials of the prototypes are shown in Table I. A schematic of the microchamber prototypes is shown in Fig. 1. In addition to the microchamber prototypes, two large-volume (LV) prototypes were used to investigate these polarity effects in larger-volume chambers. These custom LV chambers were developed by Standard Imaging for an investigation of ionization chamber effective point of measurement by McEwen\ et\ al.\(^8\). The custom LV chambers were identical in design to the commercial version of the Exradin A2 with the exception of the smaller collecting electrode outer diameter and materials. These chambers were chosen for this investigation because the only difference in design between the two LV prototypes was the material of the collecting electrodes. The LV prototype S/N 60613 and S/N 60612 contained collecting electrodes composed of C552 plastic and aluminum, respectively. This provided an opportunity to isolate the effects of collecting electrode materials on larger-volume chambers.

Saturation curves were measured using the UWADCL Theratron 1000 $^{60}$Co irradiator. Measurements were performed with the microchambers positioned perpendicular to the central axis of the radiation beam at a distance of 100 cm from the source with a field size of (10×10) cm\(^2\) at the center of the chamber volume. Irradiations were performed with the chamber in either a (50×50×47) cm\(^3\) water tank at a depth of 5 cm in water or in the absence of the water tank with the chamber in air. Measurements were performed to ensure that the relative polarity effects of a chamber were consistent in air and water.

In order to apply the desired range of applied voltages, a MAX 4000 electrometer (Standard Imaging, Middleton, WI) was altered to allow for the addition of an external voltage supply. A Harshaw high-voltage (HV) power supply was used to provide a range of voltages between 10 and 600 V. The outer wall of each chamber was held at ground while the collecting and guard electrodes were biased to the voltage

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**Table I.** Ionization chamber prototypes, and the corresponding collecting volume, inner diameter (ID) and outer diameter (OD) of the wall, and OD of the collecting electrode. The J1 and J2 prototypes were created specifically for this work and are not sold commercially. The LV prototypes are altered versions of the commercial Exradin A2 and are described in detail by McEwen\ et\ al.\ (Ref. 8).

| Custom prototype model | S/N     | Collecting volume (cm\(^3\)) | Wall Material | ID/OD (mm) | Electrode Material | OD (mm) |
|------------------------|---------|-------------------------------|---------------|------------|-------------------|---------|
| J1                     | 1, 2, 3, 4, and 5 | 0.014                         | low-Z plastic | 3.3/4.3    | low-Z plastic     | 0.75    |
| J2                     | 1, 2, 3  | 0.015                         | low-Z plastic | 3.3/4.3    | low-Z plastic     | 0.75    |
| LV1 (Ref. 8)           | 60612   | 0.53                          | C552          | 9.5/11.4   | Aluminum          | 1.0     |
| LV2 (Ref. 8)           | 60613   | 0.53                          | C552          | 9.5/11.4   | C552              | 1.0     |

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of interest. The electrometer was used in conjunction with Standard Imaging’s MAX COMM™ Version 2 software to acquire current readings at a sampling rate of 2 Hz.

For each saturation curve, the microchamber was irradiated for 20 min at an applied voltage of ±300 V corresponding to the polarity of the curve to be measured. For all saturation curves, measurements were performed during negative and positive charge collection, with voltages ranging from 10 to 600 V. At each of the applied voltages, the chamber was irradiated for 10 min allowing for 5 min of pre-irradiation followed by 5 min of data acquisition. During data collection, the atmospheric pressure and the temperature of the air or water were monitored, and a temperature and pressure correction was applied to each data set.

Saturation curves were created to demonstrate the chamber response as a function of the applied voltage. For all saturation curves, the average chamber response at each applied voltage was normalized to the average response of the chamber when negative charge was collected at a polarizing voltage of +300 V. Once the behavior for each chamber was established, a series of controlled investigations were performed to isolate the cause of the polarity effects.

2.A. Stem effects and cable irradiation

The magnitude of microchamber polarity effects has been shown to vary with the radiation field size. The irradiated portion of a chamber’s stem and triaxial cable will often vary as a function of radiation field size. Since the signal collected by small-volume chambers is significantly less than larger-volume chambers, the relative contribution to the chamber response due to extracameral effects, such as stem and cable irradiations, is larger. To investigate extracameral effects as a source of microchamber voltage-dependent polarity effects, a series of investigations were performed with the J1 prototype 3, which initially demonstrated voltage-dependent polarity effects (see Sec. 3.A). If extracameral effects were the primary source of the voltage-dependent polarity effects, reducing the volume of stem and cable irradiated should, in theory, significantly reduce the polarity effects.

To isolate the effect of cable irradiation, the chamber was placed at the center of the radiation field and irradiated with field sizes ranging from (5×5) to (20×20) cm² at the center of the chamber volume. Since the total length of the chamber’s stem was 4 cm, the primary variable was the length of the cable irradiated. To isolate the effects of stem irradiation, the chamber response was measured in a (10×10) cm² field, with the center of the chamber collecting volume in the center of the field and at the edge of the field.

2.B. Chamber assembly and contamination

The J1 prototype 3 was also used to investigate the effects of chamber assembly and contaminants such as dust and oil on the chamber behavior. The chamber response was measured after the electrodes and the insulating material were removed from the chamber and reassembled, and again after the shell of the chamber was cleaned and compressed air was used to remove any dust or loose contaminants on the surface of the insulators and electrodes. Furthermore, the chamber was disassembled, and the electrodes and the insulating materials were washed in an ultrasonic cleaner. The components were dried, the chamber was reassembled, and the chamber response was measured.

2.C. Presence of high-Z materials

Investigations dedicated to the effect of high-Z materials on microchamber response were divided into two parts: (1) to determine if high-Z materials were visible in chambers exhibiting voltage-dependent polarity effects, and (2) to introduce high-Z materials into the collecting volume of a well-behaving microchamber to determine if the high-Z material caused voltage-dependent polarity effects.

In Sec. 2.B, the presence of loose high-Z materials would have been eliminated in the disassembly and cleaning of each chamber component. A chemical analysis of the entire chamber would be required to definitively determine if any high-Z materials were present in the chamber composition. However, radiographs that were taken of the chambers showed no high-Z contaminants within the chamber materials. To introduce high-Z materials into the collecting volume of a microchamber, the collecting electrode of J1 prototype 5, which demonstrated mild voltage-dependent polarity effects, was coated with a thin layer (less than 0.5 mm thick) of a silver epoxy paste, TIGA 901 resin (Resin Technology Group, Easton, MA). The TIGA 901 formulation was sold as a two-part silver epoxy adhesive formulation composed of roughly 80% refined pure silver and 20% epoxy resin. For typical applications such as electrical bonding and sealing, the resin and hardener are mixed to cure the epoxy; however, to ensure that the silver could be removed from the collecting electrode after the experiment, only the TIGA 901 silver paste was used in this work. Saturation curve measurements were performed for the chamber with the collecting electrode coated in high-Z epoxy.

2.D. Electrode and insulator isolation

To isolate the voltage-dependent polarity effects to a specific electrode or insulator, individual components were swapped between the J1 prototypes 2 and 4 and between the LV prototypes 60613 and 60612 and the chambers were recharacterized. To swap the chamber components, the shell of each chamber was removed. The components of interest in each prototype were removed and placed in the other corresponding prototype. After each alteration, the shells were replaced. The response of each chamber was measured at a subset of positive applied voltages.

2.E. Potential difference between the guard and collecting electrode bias

Boag9 and Kim et al.10 demonstrated that a potential difference between the bias of the collecting electrode and guard electrode could distort the electric field lines within
the collecting volume and ultimately affect the chamber response. However, little work has been done to investigate the prevalence of this effect in commercial ionization chambers. For the chambers examined in this work, it is possible that a difference in conductance between the two electrode materials created a difference in the bias of the electrode surfaces, producing a voltage-dependent polarity effect. This effect would be more significant in small-volume chambers where distortion of the electric field lines would create a greater relative change in the collecting volume of the chamber. Sections 2.E.1 and 2.E.2 investigate the validity of this theory.

2.E.1. Reducing the potential difference between electrodes

Due to limitations in the ability to accurately measure the conductance of controlled and continuous points along the electrodes, an indirect method was developed to isolate the conductance of the electrodes as a cause of the behavior. To alter the conductance of the electrodes, a thin layer of graphite, called Electrodag 154® (Ladd Research, Williston, VT) was painted on the surface of the electrodes of interest. Within the J1 prototypes, the Electrodag was painted on the outside edge of the guard electrode. For the LV prototypes, the surface of the aluminum collecting electrode within chamber 60613 was coated with Electrodag. Saturation curves were measured for these conditions.

2.E.2. Inducing a potential difference between electrodes

To further demonstrate that the potential difference between the guard and collecting electrodes could cause the voltage-dependent polarity effects exhibited by microchambers, the behavior of a J2 microchamber prototype and a A12 Farmer-type chamber (Standard Imaging, Middleton, WI) was characterized with induced potential differences between electrodes. To create a potential difference between the guard and collecting electrodes of each chamber, an external voltage supply was introduced into the guard electrode circuit, independent of the collecting electrode circuitry. The conducting shield of the cable that was attached to the guard electrode of the chamber was separated from the triaxial cable, routed through a battery, and threaded back into a triaxial cable, as shown in Fig. 2. The outer conducting shield and central conductor of the cable that were attached to the shell and collecting electrodes of the chamber, respectively, were routed through a wire and back into the cable introducing no additional voltage. Therefore, the shell and collecting electrodes were not altered by the battery. The battery and additional wires were placed in a metal box to isolate and shield the signal path.

Two batteries were used, a 9 and 1.5 V battery, introducing a voltage difference of ±9.5 and ±1.64 V, respectively. Saturation curves were measured for electrometer-applied-voltages ranging from ±10 to ±300 V with the battery positioned to add positive voltage to the applied bias of the guard electrode. When the guard electrode was positively biased (for negative charge collection), the addition of the 9 V battery supplied the guard electrode with a total-applied-voltage ranging from 19.5 to 309.5 V. Conversely, for positive charge collection, the addition of the 9 V battery supplied the guard electrode with a total-applied-voltage ranging from 0.5 to 290.5 V. For both polarities, the applied bias of the guard electrode with respect to the collecting electrode was altered by 3% for electrometer-applied-voltages of 300 V and by 95% for electrometer-applied-voltages of 10 V. Similarly, the addition of the 1.5 V battery altered the total-applied-voltage to the guard electrode with respect to the collecting electrode by 0.5% and 16% for electrometer-applied-voltages of 10 and 300 V, respectively.

2.F. Simulated voltage-dependent volume effect

The mechanical volume of an ionization chamber is not an accurate representation of the collecting volume of the chamber. It has been shown that the calculated electric field in the chamber cavity may be used to determine the collecting volume of the chamber by defining the electric field lines. In this work, ionization chambers were modeled with comsol Multiphysics® finite element analysis software (using the AC/DC Electrostatic Application Module 3.5a) to simulate the effect of a potential difference between electrodes on electric field lines and collecting volume definition. A change in the collecting volume would alter the chamber response; thus, any change to the collecting volume that was voltage- and polarity-dependent would result in a corresponding voltage-dependent polarity effect. To simulate the magnitude of this phenomenon, ionization chambers were modeled with a potential difference between electrodes for a variety of applied voltages and polarities. The relative change in the collecting volume was analyzed to quantify the relationship between the polarity effects and the size of the collecting volume.

The collecting volumes of the J2 microchamber and the Exradin A12 Farmer-type chamber were modeled. The shell electrodes were set to ground (0 V) and the collecting electrodes were set to a bias of ±300 V. The bias of the guard electrodes varied from +160 to +440 V (±47% of +300 V). Simulating the bias of the guard at ±47%, ±19%, and ±3%
2.G. Measured collecting volume threshold

The relationship between collecting-volume size and microchamber polarity effects was investigated to determine if a volume threshold exists at which microchamber voltage-dependent polarity effects begin to occur. Three additional shell electrodes were constructed for the J1 microchamber prototype. The size of the shell electrodes varied, producing collecting volumes ranging from 0.018 to 0.06 cm$^3$ while maintaining roughly the same inner-radius-to-length ratio. Saturation curve measurements were performed first with the original J1 shell (collecting volume of 0.014 cm$^3$). The shell was removed and reattached and the measurements were repeated to ensure that the act of placing a new shell on the chamber would not significantly affect the chamber behavior. The remaining shells were placed on the chamber and saturation curve measurements were performed.

3. RESULTS

3.A. Initial prototype characterization

The initial saturation curves measured for each of the J1 microchambers showed varying chamber behavior among the five prototypes. As shown in Fig. 3, the magnitude and variation of the polarity effects varied among the chambers; however, the behavior of each individual chamber was consistent. These results are indicative of the behavior demonstrated by commercial microchambers. In prototypes 3 and 4, the magnitude in the polarity effects was highly voltage dependent and the inverse proportionality between chamber response and applied voltage was present. Lesser degrees of this effect were seen in prototypes 1 and 2.

The initial saturation curves measured for each of the LV prototypes showed varying chamber behavior between the two prototypes. As shown in Fig. 4, the LV2 60613 prototype with electrodes composed entirely of C552 showed typical ionization chamber behavior with minimal polarity effects. The LV1 60612, containing a collecting electrode composed of aluminum, showed the undesirable voltage-dependent polarity effects seen in microchambers. The voltage-dependent effects

![Normalized saturation curves measured for J1 prototypes. All data were normalized to the average signal received when the chamber was biased to a polarizing voltage of +300 V (negative charge collection).](image-url)
were significant enough to cause an increase in chamber response with decreasing voltage during negative charge collection. This inverse proportionality between chamber response and applied voltage is in contradiction to the expectation that the chamber response would decrease with decreasing applied voltage where ion recombination occurs. This indicates the presence of an additional phenomenon that competes with ion recombination creating voltage-dependent polarity effects.

3.B. Stem effects and cable irradiation

The voltage-dependent polarity effects exhibited by J1 prototype 3 during the initial saturation curve measurements did not significantly change with variations in the radiation beam field size or chamber placement within the field, as shown in Table II. The percent difference between the chamber response measured at applied voltages of positive 300 and 35 V was relatively consistent with radiation field sizes ranging from (5 × 5) to (20 × 20) cm². The relative chamber response was also consistent for chamber placements at the center of the field (entire chamber stem irradiated) to the edge of the field (only the collecting volume irradiated). This suggests that the increase in chamber response with decreasing applied voltage is independent of the length of cable and stem irradiated.

3.C. Chamber assembly and contamination

A small change in chamber response is expected with the disassembling and assembling of an ionization chamber. The exact fit and assembly of each chamber component may affect the collecting-volume size and shape and the strength of the induced electric field inside the chamber as a function of applied voltage. In all cases, cleaning and reassembling the components of the J1 prototype 3 had a negligible effect on the voltage-dependent polarity effects of the chamber. As shown in Table III, the percent difference between the chamber response measured at applied voltages of positive 300 and 25 V demonstrated that the increase in chamber response with decreasing voltage persisted after each round of cleaning and assembly. This investigation indicates that neither contaminants on the surface of the chamber components nor electrical connections created during the assembly of that chamber contribute to the variability in chamber response as seen between the J1 chamber prototypes.

3.D. Presence of high-Z materials

As shown in Fig. 5, coating the tip of the collecting electrode of J1 prototype 5 with the high-Z silver epoxy did not cause the chamber to exhibit greater polarity effects. In fact, the chamber signal exhibited slightly less voltage-dependent polarity effects after the silver was applied. These results

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**Table II.** The percent difference between the response of the J1 prototype 3 at applied voltages of +300 and +35 V measured for field sizes ranging from (5 × 5) to (20 × 20) cm² at the center of the chamber volume. Measurements were performed with the chamber collecting volume in the center of the radiation field and at the edge of the radiation field with the stem and triax cable outside of the radiation field.

| Prototype 3 | Percent difference ($I_{+300V}, I_{+35V}$) (%) |
|-------------|---------------------------------------------|
| Placement of chamber collecting volume | Field size (cm²) |
| Center of radiation field | 5 × 5 | +0.45 |
| | 10 × 10 | +0.51 |
| | 15 × 15 | +0.50 |
| | 20 × 20 | +0.45 |
| Edge of radiation field | 10 × 10 | +0.48 |
suggest that high-Z materials are not the primary source of voltage-dependent polarity effects in microchambers.

3.E. Electrode and insulator isolation

Since the anomalous behavior of these microchamber prototypes was not significantly altered by chamber stem and cable irradiation, contaminants, chamber assembly, or high-Z materials, experiments were performed to trace the voltage-dependent polarity effects to an individual chamber component. Individual components were swapped between the J1 prototype 4 (which exhibited voltage-dependent polarity effects, see Fig. 3) and the J1 prototype 2 (which exhibited voltage-independent polarity effects and no inverse proportionality between chamber response and applied voltage). The characterization of the chambers after each component was swapped is shown in Fig. 6(a).

The behavior of the polarity effects of the chambers most closely followed the guard electrode, with some reliance on the collecting electrode. These results suggest that for these prototypes, the voltage-dependent polarity effects were primarily caused by a characteristic of the guard electrode, with some reliance on the relation between the guard and collecting electrodes.

For the LV investigation, the collecting and guard electrodes were examined, and the results are shown in Fig. 6(b).

While the guard electrode had a negligible effect on the chamber behavior, the behavior of the chambers was significantly altered by swapping the collecting electrodes. The voltage-dependent polarity effects followed the aluminum electrode. With the C552 electrode, the percent difference between the chamber response at applied voltages of +300 and +50 V was −0.6% and −1.1% for 60613 and 60612, respectively. With the C552 collector and the same guard electrode (from the 60612 assembly), the percent difference in response for the two chambers was nearly identical at −1.1% and −1.1% for 60613 and 60612, respectively. Thus, the relative chamber response was impacted primarily by the collecting electrode, but the relationship between the collecting electrode and the guard electrode also played a role in the creation of polarity effects.

In the final characterization, saturation curves were performed for each of the LV prototypes with the collecting electrodes swapped as shown in Fig. 7. These curves ensured that the method of spot checking specific applied voltages based on initial saturation curve characterization was an adequate method for determining polarity behavior patterns.

3.F. Potential difference between guard and collecting electrode bias

3.F.1. Reduction in voltage-dependent polarity effects

The J1 prototypes containing graphite-coated guard electrodes and the LV2 60613 with the graphite-coated aluminum electrode exhibited improved behavior. The normalized saturation curves measured with the original and graphite-coated electrodes for the J1 prototype 3 and LV2 60613 are displayed in Figs. 8(a) and 8(b), respectively. As the applied voltage decreased, the graphite coating caused the chamber response to decrease during negative charge collection and increase during positive charge collection. The magnitude and slopes of the curves were brought into better agreement and the voltage-dependent charge collection were reduced.

For the LV2 60613, the aluminum collecting electrode may have oxidized over time causing a reduction in the conductance of the electrode surface with respect to the C552 guard electrode. An industrial process exists, called chromate conversion coating, or iridite, for any bare aluminum components which need to stay conductive. This process was not performed for the LV2 60613 aluminum electrode. Coating the outside of the oxidized aluminum with graphite improved the conductance and reduced the potential difference between
the collecting electrode and the guard electrode. These results agree with similar findings from Boag et al.\(^\text{12}\) In the case of the J1 prototypes, the lack of conductance of the guard electrode with respect to the collecting electrode was most likely a result of the manufacturing process of the low-\(Z\) plastic.

During positive charge collection, the original saturation curves did not exhibit an increase in chamber response with decreasing voltage. Therefore, it was less apparent if voltage-dependent polarity effects were present for positive charge collection. This investigation demonstrated an insightful graphite-induced change in chamber response for positive charge collection. This has not been reported in the literature and could lead to errors in chamber characterization when only positive charge is collected. In the case of the J1 prototype 3, traditional ion recombination correction methods would overestimate the contribution of ion recombination to the chamber collection inefficiency during positive charge collection. This work emphasizes the importance of characterizing a chamber response to both polarities to accurately assess a chamber’s behavior, as suggested in AAPM’s TG-51 addendum.\(^\text{6}\)

### 3.F.2. Induction of voltage-dependent polarity effects

The saturation curves measured for the J2 prototype with the guard electrode at various applied voltages are shown in Fig. 9(a). The original saturation curves did demonstrate voltage-independent and voltage-dependent polarity effects; however, the voltage-dependent effects were very small. With the addition of the 1.5 V battery, voltage-dependent effects were produced which were large enough to create an inverse proportionality between the chamber response and the applied voltage during negative charge collection. With the 9 V battery, the polarity effects became even greater.

Similar results were seen with the Farmer-type chamber as shown in Fig. 9(b). However, with this large-volume chamber, the effect of the potential difference between the guard and the collecting electrodes was less significant by approximately a factor of ten when compared to the microchamber. With the addition of the 1.5 V battery, a slight voltage-independent polarity effect occurred between the two saturation curves.

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**Fig. 6.** A graphical representation of the percent difference between chamber response for (a) the J1 prototypes 2 and 4 at applied voltages of +300 and +25 V and (b) the LV prototypes 60612 and 60613 at applied voltages of +300 and +50 V after a series of chamber alterations. Data measured for each prototype are represented by solid circles and dashed squares, respectively.

**Fig. 7.** Same as Fig. 4 except for (a) the LV2 S/N 60613 chamber with the aluminum collecting electrode of the LV1 S/N 60612 chamber and (b) the LV1 S/N 60612 chamber with the C552 collecting electrode of the LV2 60613 chamber.
Saturation curves measured for the (a) J1 prototype and (b) LV2 S/N 60613 chambers before (represented with solid lines) and after (represented with dashed lines) the guard electrode and collecting electrode, respectively, were coated with graphite. Each data point was normalized to the average negative charge collected before the guard was coated with graphite at an applied voltage of +300 V.

With the introduction of the 9 V battery, an increased polarity effect was measured, which was voltage-dependent.

3.F.3. Simulated voltage-dependent volume effect

Figure 10 shows the comsor generated electric field in a generic microchamber for three bias setups. Each chamber diagram displays the cross section through the center of the chamber. Since cylindrical ionization chambers are axially symmetric, only half of the cross section is required to reconstruct the three-dimensional electric field inside the chamber volume. In each of the three chamber simulations in Fig. 10, the shell electrode was held at ground (0 V) and the collecting electrode was set to a bias of +300 V. The bias of the guard electrode was varied from +290 to +310 V. The colors inside of the collecting volume represent the contoured normalized electric field. The dark red line represents the electric field line above which all of the electric field lines run from the shell electrode to the collecting electrode. Below the dark red line, the electric field lines run from the shell electrode to the guard electrode. Therefore, the dark red line represents a theoretical boundary defining the collecting volume of the chamber. With the bias of the guard lagging that of the collecting electrode, the collecting volume of the chamber was increased. Likewise, when the bias of the guard exceeded that of the collecting electrode, the collecting volume of the chamber was decreased.

With a potential difference between the electrodes, a voltage-dependent change in the collecting volume was simulated for both the J2 microchamber and Exradin A12 Farmer-type chamber. The results are shown in Fig. 11 for the microchamber (circles) and the Farmer-type chamber (squares). For both chambers, the change in volume was inversely proportional to the change in the magnitude of the bias of the guard. In other words, as the bias of the guard increased with respect to the collecting electrode, the collecting volume of the chamber decreased. The magnitude of the volume change varied with polarity. The reason for this can be seen in Fig. 10, which demonstrates that changes in the bias of the guard electrode created complex changes in

![Graph showing simulated voltage-dependent volume effect](image)

Fig. 9. Saturation curves measured for (a) a J2 prototype and (b) an Exradin A12 Farmer-type chamber with an addition of 0, 1.5, and 9 V battery to the applied bias of the guard electrode with respect to the collecting electrode shown in blue, green, and red, respectively. Each data point was normalized to the average negative charge collected for each battery setup at an applied voltage of +300 V.
The normalized electric field simulated inside a simplified J1 microchamber model. Each diagram displays one half of a cross section through the center of the chamber. The electric field is bound by the inside surface of the wall electrode. The large and small gray electrodes represent the collecting and guard electrodes, respectively. The red line represents the theoretical boundary defining the collecting volume of the chamber, above which all electric field lines run from the wall electrode to the collecting electrode. Below the red line, the electric field lines run from the wall electrode to the guard electrode. The wall electrode was set to ground, the collecting electrode was biased to +300 V, and a guard electrode was biased to +290, +300, and +310 V, from left to right.

### Results

#### Electric Field Lines

Electric field lines which were dependent on the polarity of the chamber.

For a given potential difference between the bias of the guard with respect to the collecting electrode, the magnitude of the induced volume change was approximately a factor of 10 greater for the microchamber when compared to that of the Farmer-type chamber. This indicates that the potential difference in electrode bias found in microchambers may be present in larger-volume chambers, but it is often unobservable because the resulting relative change in collecting volume is much smaller for larger-volume chambers. These results agree well with the experimental results in Sec. 2.E.2. In both investigations, the voltage-dependent polarity effects were a factor of 10 greater for the chamber with a collecting volume that was 36 times smaller.

#### Measured Collecting Volume Threshold

The J1 prototype saturation curves measured with each of the shell sizes are shown in Fig. 12. With the smallest shell size, the chamber exhibited voltage-dependent polarity effects. As the shell size, and thus the collecting volume, increased, the polarity effects were reduced. With the largest shell, which produced a collecting volume of 0.06 cm³ (equivalent to commercially available scanning chamber volumes), the voltage-dependent polarity effects were not observable. The behavior was inversely proportional to the volume of the chamber, and it indicates that there is a threshold for each chamber design at which the voltage-dependent polarity effects either begin to occur or are observable. For the J1 prototype 5, the volume threshold was between 0.026 and 0.06 cm³ for the measurement setup specified in this work. This investigation further demonstrates that...
significant voltage-dependent polarity effects may not be observable for larger-volume chambers with similar collector-guard assemblies as microchambers which do exhibit the behavior. These results coincide with the decision made by the AAPM TG-51 addendum\(^6\) to provide reference-class data for chambers with a collecting volume greater than 0.05 cm\(^3\) due to an increase in anomalous polarity and ion recombination effects seen with smaller-volume chambers.

### 4. CONCLUSION

This work eliminated several sources of voltage-dependent polarity effects in microchambers including stem and cable irradiation, chamber assembly, contaminants, and high-Z materials. Four investigations were presented which demonstrate that the potential difference between the collecting electrode and guard electrode is a primary source of these polarity effects.

First, the voltage-dependent polarity effects were empirically isolated to either the guard electrode or the collecting electrode of the chambers investigated. A reduction in polarity effects was achieved by coating the electrodes that were causing the behavior with Electrodag®. These results suggested that an electric potential difference between the guard and collecting electrodes, caused by an inequality in the electrode conductance, produced the measured polarity effects.

A methodology was developed to induce voltage-dependent polarity effects by altering the applied voltage to the guard electrode with respect to the collecting electrode. A constant potential difference between the electrodes caused significant polarity effects in the microchamber and Farmer-type chamber investigated. As the potential difference between electrodes increased, the voltage-dependent polarity effects increased, inducing an inverse proportionality between chamber response and applied voltage during negative charge collection. The induced polarity effects were an order of ten times greater for the microchamber investigated when compared to those of the Farmer-type chamber.

The voltage-dependent polarity effects in chamber response were also modeled with cosmostat simulations. The bias of the guard electrode of the chambers was set to varying percentages of the bias of the collecting electrode. The simulated collecting volumes varied depending on the potential difference of the electrodes and physical chamber size. Reducing the bias of the guard electrode with respect to the collecting electrode increased the collecting volume. Similarly, increasing the bias of the guard electrode with respect to the collecting electrode decreased the collecting volume. The relative change in the collecting volumes due to a potential difference between electrodes was also approximately ten times greater for the microchamber when compared to that of the Farmer-type chamber.

Finally, shell electrodes of varying sizes were manufactured for a microchamber prototype. Measurements demonstrated that the extent of the voltage-dependent polarity effects were inversely proportional to the size of the collecting volume of the chamber. For the J1 model investigated, the polarity effects which were present with the smaller shell electrodes became negligible once the collecting volume reached that of a typical scanning chamber (0.06 cm\(^3\)).

These investigations illustrate why these polarity effects are only observed in chambers with small collecting volumes. A given potential difference between electrodes will have a much smaller relative effect on the collective volume of a larger-volume chamber. In order to use microchambers in reference dosimetry, the potential difference between the guard and collecting electrodes must be eliminated to meet the ion recombination and polarity requirements of the TG-51 addendum.\(^6\) A wide range of tests are not needed to demonstrate that the bias difference has been eliminated. An investigator just needs saturation curves (I vs V or I/V) at both polarities for a single field size and dose rate. However, further investigations are required to demonstrate that the effect of a potential difference between electrodes on chamber response is constant as a function of beam energy and dose rate.

### ACKNOWLEDGMENT

The authors would like to thank Malcolm McEwen for providing the custom LV ionization chambers used in this work.

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