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Calibration of HDR ^{192}Ir Source Air-Kerma Strength During Time Linearity Assessments

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Abstract

A common method of a new HDR source calibration is to measure a maximum ionization current (I_{max}) using a well ionization chamber, in which the ^{192}Ir source travels along the chamber axis in the spatial domain. The source's air-kerma strength (S_K) can be determined from the measured I_{max}. In this work, an approach for routine calibration of the air-kerma strength of an HDR ^{192}Ir source in the temporal domain using integrated charge measurements with a well ionization chamber is presented. The charge Q (t) is measured as a function of time (t) for different dwell times at a sweet spot position in the well ionization chamber. The air-kerma strength is obtained from the slope (dQ/dt) of charge linearity measurement derived from the relationship between total ionization charge and time. This paper compares this method with the commonly used calibration approach based on measuring the maximum ionization current I_{max} in the well chamber. The agreement between these two methods of calibrating the ^{192}Ir source over the past several years is good and differences are less than 1%, the key finding of this study. The effect of the sweet spot range in the chamber is measured and the transit time is analyzed. New dQ/dt data over the past few years are presented. This paper provides detailed data on the sweet spot regions, transit time, and sensitivities for two types of well-type ionization chambers, and discusses the application in HDR ^{192}Ir source exchanges. This dQ/dt method provides additional support to ^{192}Ir sources calibration and verification.

Keywords

Brachytherapy, HDR Source, Calibration, Determination, Air-Kerma Strength, Well Chamber, Sweet Spot

1. Introduction

The primary goal of source calibration is to verify that the air-kerma strength of a radioactive source is consistent within the assigned tolerance, with the value specified in the vendor's calibration certificate [1]-[6], while also maintaining traceability to national or international standards. HDR units, which typically use Iridium-192 (^{192}Ir) sources for clinical application [7], require calibration because of the relatively short half-life of 73.83 days. Consequently, these sources are typically replaced three to four times a year to ensure efficient treatment de brachytherapy livery while maintaining reasonable decay times. This source exchange schedule has been consistently implemented throughout this study period. Additionally, sources with a long or short half-life may need regular or periodic calibration.

It is recommended that measurements be performed at clinical sites each time a new source is exchanged [1]-[6] [8] [9]. This onsite measurement ensures that the source's air-kerma strength is accurately determined, thereby verifying the certificate provided by the vendor. Calibration is especially important because any errors in air-kerma strength can directly impact patient outcomes.

The calibration of brachytherapy sources is critical for achieving high-precision dosimetry in treatment delivery. Well chambers, which are specialized instruments designed for use in brachytherapy dosimetry, are considered the gold standard for clinical calibration of small, sealed radioactive sources [10]-[14]. These chambers are particularly advantageous for calibrating brachytherapy sources through precise measurements of ionization generated by the air-kerma strength of the radionuclide. The specifications for brachytherapy dosimetric devices, including well chambers, are outlined in standardized recommendations such as IEC 62467-1:2009 [9] [10], which recommend complete and traceable calibration methods for HDR ^{192}Ir sources and establish the guidelines for the calibration of radiotherapy equipment.

Well chambers are used in conjunction with electrometer, which can measure ionization current or charge. The combination of the well-type ionization chamber and an electrometer provides an accurate and reliable means of measuring the air-kerma strength of the radioactive source. Both well chamber and electrometer are calibrated by an Accredited Dosimetry Calibration Laboratory (ADCL) in the United States to ensure traceability to national standards [1]-[4].

During the measurement process, the source is moved along the axis of the well chamber. In current mode, the electrometer directly measures the ionization current as the source moves through the chamber, where the chamber's response to the radioactive source can be maximized [9]-[12]. The maximum ionization current corresponds to the optimal response position, known as the sweet spot, of the new source in the well chamber. This maximum current is used to derive the air-kerma strength of the new HDR ^{192}Ir source [9] [11] [12]. The maximum ionization current should be corrected to standard conditions, such as temperature and pressure, and adjusted for any background radiation as a well chamber used in HDR brachytherapy is vented to environment [15]-[18].

In a well-type ionization chamber, the current can be directly obtained by scanning the source vertically in current mode and accumulating the charge. Alternatively, in charge mode, the electrometer measures the total ionization charge produced and integrated by the source. A charge linearity measurement is typically required to check the dwell time accuracy during the source exchange [1]-[4]. A linear fitting on the charge (Q (t)) data provides a slope and intercept. Both slope and intercept have physical meaning if the measurement is chosen in a sweet spot [19]. This sweet spot is typically located along the central axis of the chamber, and achieving this position is crucial for accurate measurement. The ability to accurately calibrate HDR ^{192}Ir sources on-site ensures the precision of individual treatment. It also contributes to the overall safety and effectiveness of brachytherapy as a treatment modality [20]-[24].

This work presents a novel approach for determining an HDR ^{192}Ir source by precisely identifying and measuring the source position at the sweet spot during time-linearity assessments. Two commonly used ionization well chambers are evaluated and compared in terms of their sweet spot regions in source strength calibration.

Data collected over several years are analyzed to compare vendor-supplied calibration certificates with two independent onsite measurements performed since 2015. The results indicate that the presented calibration method is both reliable and accurate for use in clinical settings, offering a trustworthy means of validating the air-kerma strength of new HDR sources. Furthermore, the long-term data analysis presented in this work emphasizes the consistency and reliability of the calibration process over an extended period, ensuring that any variations in source strength are detectable.

2. Materials and Methods

A GammaMedplus (GMP) iX afterloader HDR unit (Varian, Mountain View, CA) equipped with an Iridium-192 (^{192}Ir) source was used for the source calibration. The ^{192}Ir source was supplied by Alpha-Omega Services, Inc. (9156 Rose Street, P. O. Box 789, Bellflower, CA) through an ongoing service contract with Varian. The source is a cylindrical with active dimensions of 0.6 × 3.5 mm^2 (diameter × height), and capsule dimensions of 0.9 × 4.57 mm^2. A 130 cm long catheter tube and applicator were connected to the GMP HDR afterloader unit. Calibration measurements were conducted using a MAX 4000 electrometer, along with IVB 1000, and HDR 1000 Plus well ionization chambers (Standard Imaging Inc., Middleton, WI). These chambers were used to collect charge or measure current produced by ionization from the HDR source. The HDR 1000 Plus well chamber has a smaller active volume of 245 cm^3, compared to the 475 cm^3 volume of the IVB 1000 well chamber. The most major difference between these two chambers is in their axial length: the HDR 1000 Plus chamber is approximately 10 cm shorter than the IVB 1000, resulting in the significant difference in volume [25] [26]. Both the electrometer and well ionization chambers are calibrated by ADCL every two years to ensure traceable and accurate measurements.

2.1. Calibration of Air-Kerma Strength by Maximum Current

The air-kerma strength was determined by measuring the maximum current in nano amperes (nA), using electrometer in current mode to eliminate potential errors such as transit time and timer inaccuracies. The source was moved into the center of the chamber through a catheter aligned along the central axis. The chamber's active volume was sufficiently large to provide an optimum ionization current and produce a maximum response. This maximum current value is used to derive the calibrated strength or activity of the source at the clinical site, accounting for factors such as temperature, pressure, and electrometer, and ion chamber calibration factors. For example, Ref. 9 suggested the direct traceability to calibrate a source in comparison with the strength provided by a source manufacturer. A calibrated well chamber[10] is recommended for reproducibility better than 2%, long-term stability within +/−1% and collection efficiency better than 99%. This maximum current method is commonly employed in clinical settings for calibration verifications of new HDR sources, it typically agrees with the air-kerma strength S_K stated on the source certificate within +/−5%, but possible within +/−3% [9]. The S_K is directly proportional to I_{max}. By measuring I_{max}, S_K in units of U (cGy·cm^2/h or mGy·m^2/h @1m) can be determined through appropriate conversion.

For very high current measurements from a high-activity HDR source, the ionization current can reach hundreds of nA. However, the charge integration approach is helpful for obtaining acceptable precision in low ionization current situations [11].

2.2. Sweet Spot and Response in Well Chambers

The sweet spot in a well chamber refers to the position along the chamber's axis where the ionization response reaches its maximum value, offering the most accurate and consistent response as defined in Section 8.2.1. of Reference 19. The first step in the calibration process is determining the sweet spot, especially for a new chamber. Measurements were taken in charge mode using an electrometer to integrate ionization charge produced by the HDR source. These measurements were performed at multiple positions along the axis of the well chamber to establish the relationship between charge and position. The sweet spot location is primarily determined by the chamber's design, but it is also influenced by the type of source and its holder. Sweet spots were identified for both the IVB 1000 and HDR 1000 Plus well chambers. All linearity measurements were subsequently taken at these sweet spot positions.

2.3. Calibration of Air-Kerma Strength by Charge Linearity in Time Domain

To further validate the source strength, the electrometer was used in charge mode to integrate ionization charges over a variety of dwell times. Measurements were performed at the chamber's sweet spot. The dwell time window was set at 1 - 40 seconds to cover the range of clinical dwell times used in HDR treatment delivery. The dwell time of 1 second was repeated three times to average short-term timing uncertainty. The repeated measurements for the longer dwell times (5 - 40 seconds) yielded identical readings. This suggests a transit time on the order of seconds, which is consistent with the linear fitting results presented. The integrated charge was plotted against the corresponding dwell time, and the data were used to assess linearity. The design of the well chamber, the type of source, and the source holder all influence the charge vs. time relationship.

A linear fit was performed on the charge vs. time data to derive the slope and intercept. The slope, which represents the rate of ionization charge accumulation over time, effectively acts as a measure of the current and can be used as a substitute for I_{max} in determining the air-kerma strength S_K of the source. Charge linearity measurement offers a reliable means of determining source strength, especially for new sources, and serves as a verification of the maximum current method. This approach provides a means of correlating ionization charge with dwell time, allowing for accurate calibration of the HDR source strength.

Although charge linearity measurements typically do not require the measurement points to be at the sweet spot, performing them there not only verifies charge linearity but also provides an additional reference for determining source strength or activity. By comparing the ionization current from the linear fit to known calibration values, the accuracy of the source's strength can be obtained independently.

Figure 1 shows a flowchart outlining two approaches to determine the air-kerma strength S_K using I_{max} or $^{Q}S_K$ using dQ/dt, where ADCL calibrated devices (well chamber, electrometer) are used alongside a barometer, and thermometer. The temperature and pressure corrections are applied to obtain the air-kerma strength.

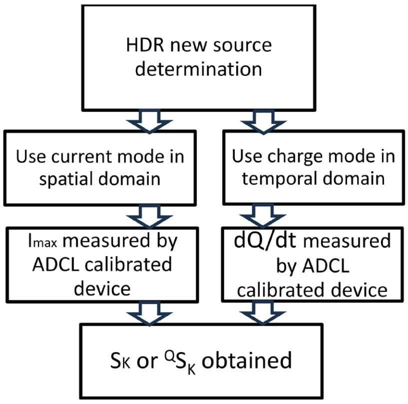
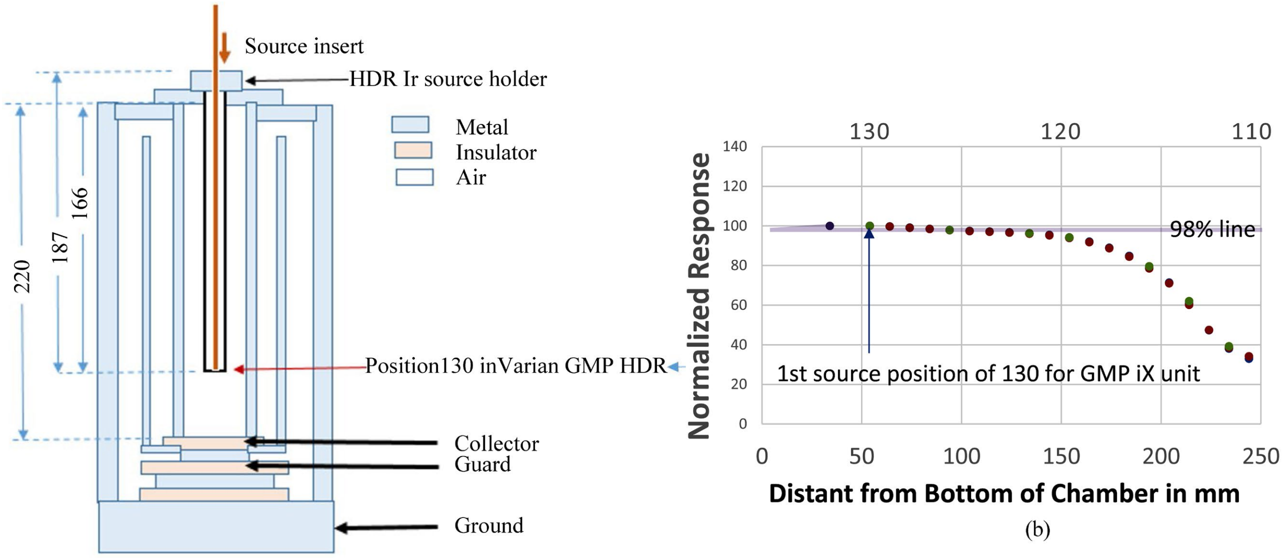


Figure 1. A flowchart to represent a process how to use I_{max} or dQ/dt to independently calibrate the air-kerma strength S_K or $^{Q}S_K$, where the ADCL calibrated device with the certificates includes well chamber, electrometer combined with barometer, and thermometer. The left part is the common approach to use the current mode with I_{max}. The right part is the proposed method to utilize the charge mode with dQ/dt. Either method can obrain the air-kerma strength.

3. Results

3.1. Range of Sweet Spots

Figure 2 illustrates the geometrical structure and ionization charge response curve along the axial direction of the IVB 1000 well chamber. Figure 2(a) displays the normalized charge response in the IVB 1000 chamber based on the dwell position of a GMP ^{192}Ir source. Two coordinates were used: one relative to the catheter tube and applicator (e.g., 130, 125, 120, 110 cm), and the other the distance from the bottom of the well chamber (e.g., 54, 94 mm). The first source position was located at a catheter length of 130 cm, approximately 54 mm from the bottom of the IVB 1000 chamber. Figure 2(b) shows the sweet spots measured for multiple sources using the IVB 1000 chamber. Using a threshold of 98% of the normalized response, the "sweet spot" range extends from 54 to 94 mm in the IVB 1000 wchamber, equivalent to 130 - 126 cm on the GMP tube scale.

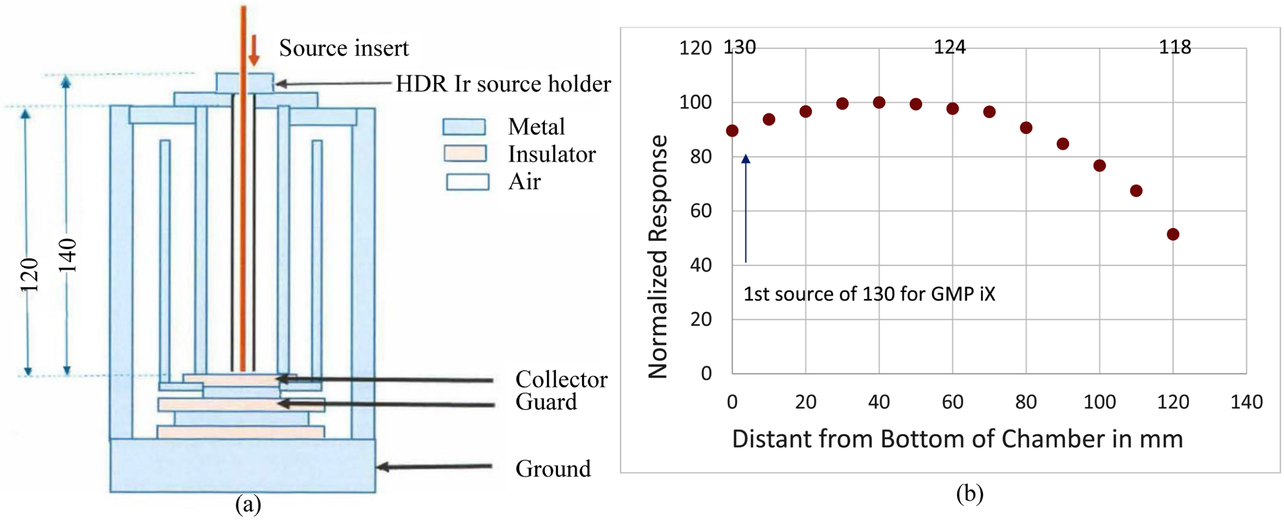


(a)

(b)

Figure 2. (a) Illustration of IVB 1000 well chamber and corresponding sweet spot position in the chamber for GMP HDR unit, the inserted graph is the same as the tilted Figure 2(b) for the position indication; (b) the sweet spot positions in the chamber, the upper x-axis (130 cm, 110 cm) is the scale in the HDR catheter and applicator length, the x-axis is the distance from the bottom of the well chamber. The y-axis is the normalized ionization charges. 98% of the maximum charge response is plotted for the eye guideline. The sweet spots were measured for different source exchanges in various colors.

In cylindrically symmetric well chambers, the primary variable determining the sweet spot is the longitudinal position along the cylindrical axis. The sweet spot range, defined as the full width at a specified percentage of the maximum signal response, can vary in size depending on the chamber type and source configuration. Clinically, the maximum current (I_{max}) is recommended for air-kerma strength or activity calibration. Here, the sweet spot is defined as the full width at 98% of the maximum charge signal response [11] [12] [19]. This definition is more conservative than the 95% recommended in Reference 19 (Page 19, Section 4.1.1).



(a) (b)

Figure 3. (a) Illustration of HDR 1000 Plus well chamber and corresponding sweet spot position in the chamber for GMP HDR unit, the inserted graph is the same as the tilted **Figure 3(b)** for the position indication; (b) the sweet spot positions in the chamber, the upper x-axis (130 cm, 118 cm) is the scale in the HDR catheter and applicator length, the x-axis is the distance from the bottom of the well chamber. The y-axis is the normalized ionization charges.

Figure 3(a) shows the relative source position and ionization charge response in the HDR Plus 1000 well chamber. The sweet spot range narrows significantly, spanning only from 50 to 70 mm (125 - 127 cm on the GMP catheter and applicator scale) as shown in **Figure 3(b)**.

Based on the data from **Figure 2(b)** and **Figure 3(b)**, the sweet spot range measures 40 mm for the IVB 1000 chamber and 20 mm for the HDR 1000 chamber. Both chambers can be utilized to achieve the maximum response in the spatial domain and the charge gradient in the temporal domain, respectively.

3.2. Linearity of Charge vs. Dwell Time

For linearity measurements, ionization charges were recorded at various dwell times, with the source positioned at 130 cm in the catheter and applicator (equivalent to 54 mm from the bottom of the sweet spot, as shown in **Figure 2**). The dwell times were set at 1, 5, 10, 15, 20, and 30 seconds, with corresponding ionization charge collections. A typical linearity plot of charge versus dwell time is illustrated in **Figure 4**. Using linear regression, the relationship was fitted with two parameters: the slope (dQ/dt) and the intercept (Q_o) for a point within the sweet spot range. Both parameters, dQ/dt and Q_o, remained constant regardless of dwell time. dQ/dt represents the change in charge over time (C/sec), indicating the current dQ/dt generated by ionization. This ionization current Io characterizes the charge collected in the temporal domain.

The linearity of charge Q(t) with dwell time t follows the linear equation:

$$Q(t) = (dQ/dt)\,t + Q_o \tag{1}$$

where dQ/dt, represents the slope (current dimension), and Q_o is the intercept (charge dimension).

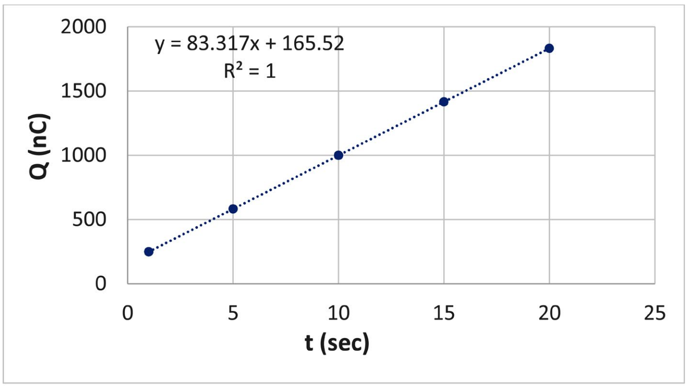


Figure 4. The charge linearity vs dwell time data with the linear regression to: Q (t) = (dQ/dt) t + Q_o; data at 130 cm (or 54 mm) taken in the IVB 1000 well chamber on 02/27/2018.

3.3. Linearity and Sweet Spot Range

Charge versus time linearity does not necessarily require the measurement to occur within the sweet spot, however the slope reflects whether the position is within that range. Figure 5 illustrates linearity data at positions at 130, 125, 115, and 110 cm, with 130 and 125-cm lying within the sweet spot range, while 115 and 110-cm fall outside. As the position moves from 130 or 125 to 115 and 110 cm, the slopes of the regression lines dramatically decrease, indicating a reduced ionization current at these locations outside the sweet spot range.

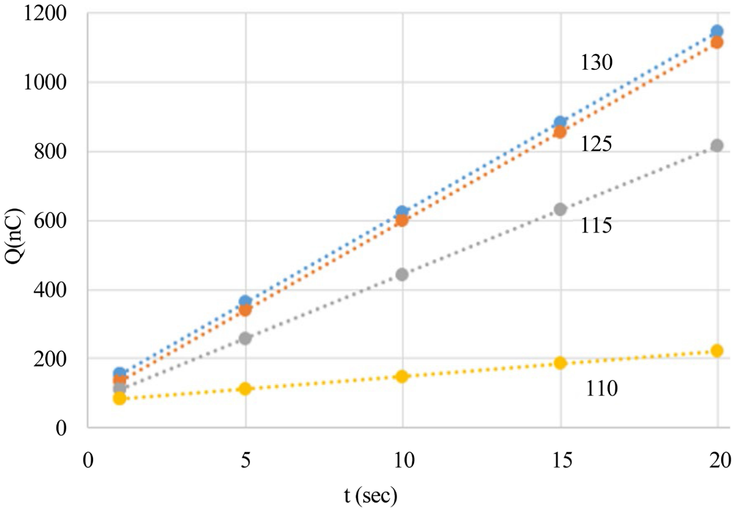


Figure 5. The data at different source positions of 130, 125, 115 and 110 cm, notice dQ/dt changes with source position in the IVB 1000 well chamber. Notice 130 and 125 cm positions are in the sweet spot region; 115 and 110 cm positions are out of the sweet spot region.

The approach of using I_{max} is widely recommended for HDR source calibration at clinical sites. This method provides a strong signal in current mode with high precision, reducing concerns about timing errors during measurements, as noted [11] [12]. Consequently, I_{max} measurements have become a routine calibration procedure at clinical sites during new source exchanges. When measurements are performed within the sweet spot range, the maximum response to ionization is consistent, whether using I_{max} in current mode or dQ/dt in integrated charge mode.

4. Discussion

Intercept Constant Q_o and Transit Time t

The intercept constant Q_o is not physically meaningful at initial condition t = 0, as the collected charge is expected to be zero prior to irradiation. This non-zero Q_o can instead be attributed to the transit time involved in the combined setup of the HDR source and chamber. The transit time t represents the effective time correction for ionization charge collection during source transit, rather than the actual travel time to and from the dwell position.

Equation (1) can be normalized by the factor dQ/dt, such that t (t) is a function of time and $t_o = t(0)$ is the initial or physical transit time. The transit time can be calculated from the linearity data by rearranging Equation (1) as:

$$t(t) = Q(t)/(dQ/dt) = t + t_o \tag{2}$$

where $t(t) = Q(t)/(dQ/dt)$ and $t_o = Q_o/(dQ/dt)$. Here, $t(0) = t_o$ at t = 0, serving as a correction factor for the effective transit time. If the current stabilizes in the well chamber, no transit time correction is necessary. However, knowing the dose received during the source's transit period is clinically relevant.

For the past several years, both I_{max} and dQ/dt were measured separately during new source ^{192}Ir exchanges at our clinical site. As mentioned earlier, I_{max} was measured directly from a sourcemoving along the central axis in current mode, and dQ/dt was obtained from linearity measurements at the sweet spot position in charge mode.

Table 1 and Table 2 summarize the measurements of I_{max} and dQ/dt using IVB 1000 and HDR 1000 Plus well chambers, respectively. Since the ionization current is proportional to the air-kerma strength, the ratio of these two quantities is the same, namely, $I_{max}/(dQ/dt) = S_k/{}^{Q}S_k$ where S_k is proportional to I_{max} and ${}^{Q}S_k$ is proportional to dQ/dt. As can be seen, the average difference between I_{max} and dQ/dt is less than 0.5% for both well chambers. While a paired t-test may indicate statistical significance, this difference is well within clinical tolerance and suggests the equivalence of the I_{max} and dQ/dt for clinical use. At clinical sites, new HDR source S_k calibration is required within a 5% tolerance of the vendor's certificate. The observed 0.5% difference easily satisfies this tolerance requirement for brachytherapy dosimetry. This difference probably come from the transit time involved in the measurement taken in the temporal domain, rather than the instantaneous time in the spatial domain. By comparison, the normalized transit time constant (t_o) is 2.00 seconds for IVB 1000 and 1.57 seconds for HDR 1000 Plus, respectively.

Equation 2 provides the value of the transit time t for the IVB 1000 and HDR 1000 Plus used. Table 1 and Table 2 clearly show the average transit time for the

IVB 1000 chamber is 2.00 +/− 0.10 sec, and the average transit time for the HDR 1000 Plus is 1.57 +/− 0.04 sec. These data were obtained at the sweet spot. The standard deviation of 0.10 sec for the IVB and 0.04 sec for the HDR 1000 Plus reflect the axial length difference of two well chambers as the IVB is 10 cm longer than the HDR 1000 Plus. The measurement precision for the HDR 1000 Plus is more statistically reliable than the IVB at this point, probably due to the smaller collecting volume in HDR 1000 Plus. The proposed method of dQ/dt for calibrating a new brachytherapy source is more efficient than the I_{max} method since a measurement of the charge verses dwell time produces dual results of the linearity and the ionization current data. This is a practically advantage for a busy clinical setting to quickly perform the recommended procedure for a new HDR source. The proposed dQ/dt method is also advantageous to calibrate low-activity brachytherapy sources since low current potentially generate a higher standard deviation in maximum current, which affects reproducibility and long term stability [11].

Table 1. The data of I_{max} (nA), dQ/dt (nA), I_{max}/(dQ/dt), $S_K/{}^{Q}S_k$, the difference in percentage between I_{max} and dQ/dt (Diff in %), and t_o (sec) using IVB 1000 well chamber. The average value and the standard deviation are also listed.

Date	I_{max} (nA)	dQ/dt (nA)	I_{max}/(dQ/dt)	$S_K/{}^{Q}S_K$	Diff in %	t_o (sec)
05/19/22	76.168	76.064	1.0014	1.0014	0.14%	1.97
11/10/21	82.504	82.174	1.0040	1.0040	0.40%	2.10
08/27/21	74.015	73.814	1.0027	1.0027	0.27%	2.11
06/07/21	67.174	67.314	0.9979	0.9979	−0.21%	2.02
02/05/21	86.889	86.964	0.9991	0.9991	−0.09%	2.09
08/06/20	88.607	88.559	1.0005	1.0005	0.05%	2.09
05/01/20	77.780	77.613	1.0022	1.0022	0.22%	2.07
12/31/19	81.131	80.980	1.0019	1.0019	0.19%	2.06
08/27/19	88.760	88.340	1.0048	1.0048	0.48%	1.97
05/17/19	89.399	89.087	1.0035	1.0035	0.35%	1.98
01/18/19	80.712	80.380	1.0041	1.0041	0.41%	1.98
12/20/18	73.910	73.654	1.0035	1.0035	0.35%	1.98
06/20/18	67.030	66.803	1.0034	1.0034	0.34%	2.05
02/27/18	83.501	83.317	1.0022	1.0022	0.22%	1.99
12/13/17	79.422	79.101	1.0041	1.0041	0.41%	2.14
09/05/17	86.239	85.764	1.0055	1.0055	0.55%	2.02
05/19/17	81.063	80.603	1.0057	1.0057	0.57%	2.00
01/10/17	85.994	85.853	1.0016	1.0016	0.16%	2.00
08/31/16	89.619	89.194	1.0048	1.0048	0.48%	1.88
05/25/16	87.937	87.361	1.0066	1.0066	0.66%	2.00
01/05/16	87.940	87.110	1.0095	1.0095	0.95%	1.87
09/03/15	87.586	87.165	1.0048	1.0048	0.48%	1.69
AVERAGE			**1.0034**	**1.0034**	**0.34%**	**2.00**
STDEV			**0.0025**	**0.0025**	**0.25%**	**0.10**

Table 2. summarizes the data of I_{max} (nA), dQ/dt (nA), I_{max}/(dQ/dt), $S_K/^QS_k$, the difference in percentage between I_{max} and dQ/dt (Diff in %), and t_o (sec) using HDR 1000 Plus well chamber. The average value and the standard deviation are also listed.

Date	I_{max} (nA)	dQ/dt (nA)	I_{max}/(dQ/dt)	$S_K/^QS_K$	Diff in %	t_o (sec)
12/09/24	65.564	65.498	1.0010	1.0010	0.10%	1.58
08/23/24	79.621	79.367	1.0032	1.0032	0.32%	1.60
05/21/24	75.751	75.914	0.9979	0.9979	−0.21%	1.62
02/05/24	79.800	79.362	1.0055	1.0055	0.55%	1.59
11/13/23	81.763	81.494	1.0033	1.0033	0.33%	1.57
08/18/23	85.526	85.131	1.0046	1.0046	0.46%	1.59
05/17/23	79.990	79.650	1.0043	1.0043	0.43%	1.58
02/13/23	79.550	79.343	1.0026	1.0026	0.26%	1.58
12/06/22	75.800	75.663	1.0018	1.0018	0.18%	1.49
08/04/22	83.782	83.699	1.0010	1.0010	0.10%	1.59
01/28/22	88.178	87.611	1.0065	1.0065	0.65%	1.54
11/10/20	82.164	81.940	1.0027	1.0027	0.27%	1.52
AVERAGE			**1.0030**	**1.0030**	**0.30%**	**1.57**
STDEV			**0.0023**	**0.0023**	**0.23%**	**0.04**

The radiation sensitivity of a well ionization chamber is defined as the ratio of ionization current to air-kerma strength in (nA/kU) (or equivalently to the apparent activity in nA/Ci), where U = 1μGy × m^2/h [25] [26]. The design goal sensitivities for an HDR ^{192}Ir source are 9.0 nA/Ci (2.2 nA/kU) for the IVB 1000 and is8.6 nA/Ci (2.1 nA/kU) for the HDR 1000 Plus, respectively [25]-[27]. Our measurements show that the average sensitivity for the IVB 1000 and HDR 1000 Plus is 8.7 nA/Ci and 8.4 nA/Ci (or 2.14 nA/kU and 2.06 nA/kU), respectively. These sensitivities are sufficient for standalone calibration of HDR ^{192}Ir sources in clinical settings.

5. Conclusion

We present HDR ^{192}Ir source calibration data using the slope of linear regression in the temporal domain at the sweet spot position, and the maximum current in the spatial domain, respectively. Excellent agreement in air-kerma strength or the apparent activity was obtained from these two different calibration methods, suggesting that the linearity of charge vs. dwell time can be used for HDR ^{192}Ir source calibration. A constant gradient from the linear regression is the ionization current measured in the temporal domain, which carries the same physical meaning as I_{max}. In addition to the linearity verification, a single measurement of charge linearity at the sweet spot can also be used for new source strength calibration. The transit time can be derived from the intercept parameter in the linear regression. Detailed data regarding the sweet spot regions, the transit time, and the sensitivities of IVB 1000 and HDR 1000 Plus well chambers are provided and discussed for use in HDR ^{192}Ir source exchanges in the clinic. This temporal calibration method is an efficient and reliable approach that can be used for on-site calibration of other HDR model units. The method can also be applied to other brachytherapy sources, especially those with weak air-kerma strength.

Conflicts of Interest

The authors have no relevant conflicts of interest to disclose.

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