Quality assurance tool for high dose rate brachytherapy

Larry A. DeWerd, Paul Jursinic,^{a)} Rebecca Kitchen,^{b)} and Bruce R. Thomadsen
Department of Medical Physics and Department of Human Oncology, University of Wisconsin, Madison,
Wisconsin 53706

(Received 23 May 1994; accepted for publication 20 October 1994)

An insert for a well ionization chamber is described for quality assurance tests for high dose rate remote afterloaders. The use of this insert over time has shown its applicability for efficient QA tests for the high dose rate afterloader. The measurement results are six times greater than the uncertainties involved for the measurements. Checks on position can be made better than 1 mm and dwell times better than 1 s. The overall measurements can be done to better than 1.5%. QA checks can be accomplished in a shorter time period with as great or better accuracy than prior film techniques.

Key words: high dose rate brachytherapy, quality assurance, Ir-192 remote afterloaders, calibration

I. INTRODUCTION

Accurate delivery of doses using a high dose rate brachytherapy, remote afterloading (HDR) system depends on knowing the strength of the radioactive source at the time of treatment, the precision and consistency of the timer, and the ability of the unit to position the source at the proper dwell location along the catheter. Periodic Quality Assurance (QA) on HDR machines is a part of the standard protocol of any user. Quality assurance tests for the accuracy of dwell positions usually use autoradiographs or mechanical rulers and video monitors, and for dwell times, a stopwatch. The strength of the source can be determined using measurements made with a calibrated chamber in precise geometric relationships to the source. These methods can be time consuming for a routine quality assurance program.

The use of a well ionization chamber for calibration of source activity has proven to be easy to use and accurate.^{1,2} This chamber includes a removable insert used to position the catheter accurately. A specifically designed quality assurance insert for this well chamber can be used to test source positioning verification, timer consistency, and a measurement of the consistency of source activity in a relatively short time period. These techniques are the subject of this paper.

II. MATERIALS AND METHODS

The standard calibration insert of the Standard Imaging well chamber² is removable and can be replaced by other inserts. (Manufactured by Standard Imaging, Inc. 6213 Middleton Springs Dr., Suite 205, Middleton, Wisconsin 53562.) A quality assurance insert, as shown in Fig. 1, consists of lead with transverse spacers of acrylic placed at a precisely known distance from the bottom of the catheter. This insert can replace the standard calibration insert for doing a QA check. The insert collimates the sensitive volume of the chamber to a narrow plane. When the source lies in that plane, the chamber responds with a large signal; when the source falls partially or completely out of the plane, the signal diminishes rapidly. Measurements reported here used an HDR source with an active length of 3.5 mm. (Nucletron MicroSelectron, Nucletron Corp., Columbia, Maryland 21045.) Other remote afterloaders can be similarly tested

with this QA insert using appropriate settings. In this investigation, the signal from the well chamber (negative charge collected, biased to 300 V) was read on a Keithley 602 electrometer, and corrected for atmospheric density.

For easy and rapid access, the chamber resides on a custom-made bracket on the wall. While the readings from such an arrangement include too much scatter generated from the wall to serve as a primary calibration,³ the measurements can be used as a consistency test for the calibration done previously in a low scatter position. For QA measurements, the system need only produce reliable, reproducible readings. However, a constant location is very important for consistent results for all the QA measurements. To evaluate the stability of the chamber as a QA device, each day that any patient received treatment using the HDR unit, measurements were made in the well chamber using the original insert, with the readings corrected for atmospheric density. Measurements spanned four sources. These series of readings were compared to signals predicted from measurements performed on the day of initial calibration for each source and then corrected for radioactive decay. The repeated calibration of the well chamber, as per the method of Goetsch *et al.*¹ showed a precision of 0.06% for one standard deviation over this same time period. The stability of the chamber's response over time was verified through a series of measurements, as in Goetsch *et al.*²

III. RESULTS

With the standard insert and the chamber mounted on the wall, separate readings were made to evaluate the sensitivity and stability of the instrument for a QA mode of operation. Figure 2 shows the daily readings for a 10 s exposure corrected for decay (using a 73.8 day half-life⁴) and atmospheric density for four sources. All readings fall within 1.5%, with most within $\pm 0.6\%$ of the initial reading at the time of calibrations. The precision in the "QA" mode could not match that of Goetsch cited above for careful calibration, but certainly proves the tool's stability in daily use.

After placing the lead QA insert, shown in Fig. 1(a), in the well chamber cavity, the catheter was inserted to the bottom of the well and locked in place; the response was then measured. The response of the chamber was measured as a function of the source position, and is shown in Fig. 3(a). As

FIG. 1. Diagrams of two versions of the quality assurance, lead insert for a well-type ionization chamber. (a) Insert with two acrylic spacers of 1 and 4 mm. (b) Modified insert with single acrylic spacer of 4 mm width.

expected, when the source approached the centers of the acrylic spacer, the chamber response increased and showed a peak as the center of the source and spacer coincided. Repetition of this measurement consistently produced the same curve. Three sets of measurements spanning 18 months all produced curves with a full width at half-maximum of $13 \text{ mm} \pm 0.5 \text{ mm}$, with the peak also falling within $\pm 0.5 \text{ mm}$ of the same location, despite disassembly and reassembly of the

tool. For checking positional accuracy, the high slope regions of Fig. 3(a) are most useful; positions 919.5 and 959.5 were used for this purpose for the insert shown in Fig. 1(a). For checking dwell time and activity, a plateau rather than a peak is desired. This is the reason that the 4 mm spacer was used to provide the plateau region centered at position 924.5 on the Nucletron unit, giving some latitude for the QA checks. After tests on the insert of Fig. 1(a), it was decided that only

FIG. 2. Percent difference in daily readings compared to that expected.

FIG. 3. Measurement of current in a well-type ionization chamber with a quality assurance, lead insert versus the position of an Ir-192 source. (a) Corresponds to the insert shown in Fig. 1(a). (b) Corresponds to the insert shown in Fig. 1(b).

one spacer was needed as shown in Fig. 1(b). Tests of the QA insert in Fig. 1(b) yielded results similar to that for the first design. The response of the chamber to this insert is shown in Fig. 3(b), where the slope point is designated as point A and the plateau point as point B. The insert of Fig. 1(a) with two acrylic spacers may be useful if the distance between steps varies with distance.

IV. DISCUSSION

A. Analysis

The response of the chamber at any position can be described by the following equations: When charge is measured,

$$Q(x,t) = K(x,t)A_0e^{(-\lambda\tau)t}/C_{tp}; \quad (1)$$

and when current is measured,

$$I(x) = K(x)A_0e^{(-\lambda\tau)}/C_{tp}; \quad (2)$$

where $Q(x,t)$ is the charge measured when the source is in position x for time t , x is the position of the source in the QA insert, and t is the exposure time, if using a gated measurement system, or otherwise the effective time, adjusted* for transit-time effects; $K(x,t)$ is the function that relates the response of the system to x and time t ; this function will be a constant for a given point of measurement; $I(x)$ is the current measured when the source is at position x ; C_{tp} is the correction for temperature and atmospheric pressure for the ionization chamber; A_0 is the source strength at the time of calibration of the Ir-192 source; τ is the time since the calibration; and λ is the decay constant of Ir-192. From Eqs. (1) or (2), $K(x,t)$ can be determined for each position of measurement:

$$K(x,t) = Q(x,t)C_{tp}/A_0e^{(-\lambda\tau)t} \quad (3)$$

or

$$K(x) = I(x)C_{tp}/A_0e^{(-\lambda\tau)}. \quad (4)$$

The variation in K with respect to position x and dwell time t can then be expressed as follows, assuming dwell time does not change with position. For charge measurements,

$$\frac{\partial K}{\partial t} \left(\frac{1}{K} \right) = \left(\frac{1}{Q} \right) \left[\frac{\partial Q}{\partial t} \right] - \left(\frac{1}{t} \right) \quad (5)$$

and

$$\frac{\partial K}{\partial x} \left(\frac{1}{K} \right) = \left(\frac{1}{Q} \right) \left[\frac{\partial Q}{\partial x} \right]; \quad (6)$$

and for current measurements,

$$\frac{\partial K}{\partial x} \left(\frac{1}{K} \right) = \left(\frac{1}{I} \right) \left[\frac{\partial I}{\partial x} \right]. \quad (7)$$

At the plateau, $\partial I/\partial x = 0$ and $\partial Q/\partial x = 0$ for a given dwell time. Therefore, any change in $K(x,t)$ involves a change in the executed dwell time, the transit time, or an anomalous decay or other change in the source. The absence of a change in $K(x)$ would eliminate a source anomaly.

At the slope position, as can be seen from Eq. (6) or (7), any change in $K(x)$, not accompanied by changes in the plateau region, is a result of a change in position.

B. Uncertainty analysis

To evaluate whether the system could detect appropriate errors in activity, timer consistency, or positioning requires determination of the uncertainties in the measurements. While explicitly a function of x and/or t , establishing K from Eqs. (1) or (2) actually makes K a possible function of x , t , A (or A_0 and $\lambda\tau$), Q , I , temperature, and pressure. The uncertainty in K from Eq. (1) becomes

TABLE I. Calculations of the positional constant $K(x, t)$ using Eqs. (3) or (4). The source strength was determined with a calibrated well-type ionization chamber. The % std. dev. = $\sigma^* 100/\text{average}$, where σ is the standard deviation. Air kerma strength is given in terms of $U_s = 1 \mu\text{Gy} \cdot \text{m}^2/\text{s}$.

Date	Source strength (U_s)	Slope K (919.5) (nA/ U_s)	Slope K (959.5) (nA/ U_s)	Plateau K (924.5) (nA/ U_s)
1 March	20.165	0.4690	0.3790	0.5084
1 March	20.059	0.4766	0.3820	0.5084
2 March	19.953	0.4647	0.3758	0.5082
4 March	19.581	0.4706	0.3792	0.5075
5 March	19.422	0.4715	0.3786	0.5088
8 March	18.838	0.4621	0.3758	0.5096
9 March	18.679	0.4636	0.3775	0.5096
10 March	18.520	0.4615	0.3771	0.5105
11 March	48.343	0.4641	0.3773	0.5086
12 March	47.865	0.4647	0.3769	0.5058
15 March	46.538	0.4687	0.3775	0.5056
18 March	45.265	0.4641	0.3784	0.5075
23 March	43.195	0.4606	0.3771	0.5084
24 March	42.771	0.4719	0.3780	0.5064
Average		0.4667	0.3778	0.5081
Std. dev.		0.0047	0.0016	0.0014
% std. dev.		1.01	0.42	0.28

$$\left(\frac{\delta K}{K}\right)^2 = \left(\frac{\delta Q}{Q}\right)^2 + \left(\frac{\delta t}{t}\right)^2 + \left(\frac{\delta A_0}{A_0}\right)^2 + (\tau \delta \lambda)^2 + (\lambda \delta \tau)^2 + \left(\frac{\delta \text{Temp}}{\text{Temp}}\right)^2 + (\delta \text{Press/Press})^2.$$

The first term on the right-hand side contains the uncertainty in the desired information, as well as the uncertainty in the measurement system (electrometer and chamber). The uncertainty due to these components are broken out as

$$(\delta Q/Q)^2 = (\delta \text{electrometer and chamber/electrometer and chamber})^2 + [\delta x(\partial Q/\partial x)/Q]^2 + [\delta \epsilon/\epsilon]^2,$$

where ϵ refers to an actual error in the timer's performance, not the transit-time effect. The last two terms of this last equation form the test items, and are thus left out of the uncertainty calculation. The values for each term are thought to be $(\delta t/t)^2 = 0.000\,001$, in the absence of a timer malfunction; $(\delta A_0/A_0)^2 = 0$, since the measurements are based only on consistency with respect to the initial calibration; $(\tau \delta \lambda)^2 = 0.000\,021$ if using 0.5 day decay increments; $(\lambda \delta \tau)^2 = 0.000\,022$ maximum toward the end of a useful source life; $(\delta \text{Temp/Temp})^2 = 0.000\,0005$; $(\delta \text{Press/Press})^2 = 10^{-8}$; and $(\delta \text{electrometer and chamber/electrometer and chamber})^2 = 0.000\,01$. When these are combined in quadrature, there is a total contribution of 0.000 055, equivalent to about 0.7%. Under worse conditions during application, this might become 1%. This is compatible with the stability measurements presented in Sec. II A with the standard insert. From this analysis, changes in the value for K greater than 1.5% may be considered significant. Repeating this analysis for the current readings gives an almost identical uncertainty.

From the slope at the 919.5 mm position, a 1 mm error in position would become a 3% change in the current-based K ,

TABLE II. Determination of $\mathfrak{B}$ and t_{transit} of Eq. (10) for eight separate measurements.

Date	$I(924)$ (nA)	$Q(924, 5 \text{ s})$ (nC)	$Q(924, 10 \text{ s})$ (nC)	$\mathfrak{B}$	t_{transit} (s)
24 May	11.780	62.85	121.90	1.003	0.32
1 June	11.170	59.70	115.70	1.003	0.33
2 June	11.030	59.45	114.10	0.991	0.44
3 June	10.890	58.15	112.20	0.993	0.38
8 June	10.260	54.95	105.80	0.991	0.40
9 June	10.080	54.65	104.45	0.988	0.48
10 June	10.180	54.75	104.95	0.986	0.45
11 June	10.160	54.05	104.50	0.993	0.35
Average				0.994	0.39
Std. dev.				0.006	0.06

or four times the measurement uncertainty. An error in the timing of an exposure would show as a change in the reading in direct proportion to the *effective duration*, that is, the combination of the dwell time and the transit time. Thus, a timing error could be due to a change in the relation between indicated "seconds" and real seconds (for proper operation, this proportionality never need be unity, only constant), a failure of the timer linearity, the introduction of some constant offset (or nonconstant offset) to the times, a change in the effective transit time, or, but less likely, a source decay anomaly. The system should be able to detect any problem that produces a 2% change in the reading (about 2.5 times the uncertainty). As a matter of fact, we have observed smaller changes in the reading tracking small changes in film results that would not normally be noticed.

C. Application on a daily basis

To determine the applicability of this approach, 14 independent trials, over 24 days, were run with the QA insert shown in Fig. 1(a). Current was measured at source positions 919.5 and 959.5 for determination of dwell position accuracy, and at position 924.5 for determination of the accuracy of source activity. Charge was measured at source position 924 for determination of dwell-time accuracy. Table I shows the results of these measurements. The calculation of K values used the half-life for iridium of 74.2 days contained in the Nucletron computer controller; the actual half-life has been shown to be 73.83 days.⁴ The $K(x, t)$ values were very reproducible over these 14 trials with a relative standard deviation of less than 1.1%. This low frequency of error occurred even though a source change was made on March 11.

At the plateau position, 924, timer accuracy can be determined by measuring the charge accumulated in the amount of dwell time set on the HDR control. The measured amount of time can be calculated from Eqs. (1) and (2) as follows:

$$Q(924, t_{\text{set}}) = Q(924) + Q(\text{transit}), \quad (8)$$

where $Q(\text{transit})$ is the reading accumulated while the source moves into, and returns from, its dwell position.

Approaching this analogously to that typical of cobalt units, define an effective transit time, $t_{\text{ef, tr}}$, such that

$$t_{\text{meas}} = \mathfrak{B}t_{\text{set}} + t_{\text{ef, tr}}, \quad (9)$$

TABLE III. Calculations of the positional constant $K(x)$ using Eqs. (3) or (4) for the single spacer of 4 mm at approximately 50 mm from the bottom of a calibrated well-type ionization chamber. The % std. dev. = $\sigma \cdot 100/\text{average}$, where σ is the standard deviation. Air kerma strength is given in terms of $U_s = 1 \mu\text{Gy} \cdot \text{m}^2/\text{s}$.

Date	Source strength (U_s)	Slope K (952) (nA/ U_s)	Plateau K (949.5) (nA/ U_s)	Slope K (947) (nA/ U_s)
18 January	34.275	0.2908	0.3776	0.3117
19 January	33.797	0.2808	0.3773	0.3260
20 January	33.479	0.2992	0.3778	0.3113
21 January	33.166	0.2855	0.3776	0.3100
21 January	33.166	0.2825	0.3776	0.3040
24 January	32.253	0.3085	0.3784	0.3243
25 January	32.099	0.2934	0.3795	0.3030
26 January	31.654	0.3006	0.3814	0.3038
7 February	28.284	0.2849	0.3788	0.3066
8 February	28.157	0.2819	0.3771	0.3111
8 February	28.157	0.2819	0.3771	0.3149
9 February	27.764	0.2836	0.3793	0.3206
11 February	27.376	0.2844	0.3778	0.3181
14 February	26.490	0.2853	0.3792	0.3206
15 February	26.368	0.2913	0.3808	0.3147
24 February	24.235	0.2829	0.3773	0.3172
Average		0.2886	0.3784	0.3136
Std. dev.		0.0081	0.0013	0.0072
% std. dev.		2.81	0.35	2.30

where $\mathfrak{B}$ is a proportionality factor that should be equal to unity if the HDR timer is accurate; $t_{\text{ef, tr}}$ is the equivalent time to account for that part of the reading produced with the source in transit going to and returning from its dwell position; and t_{meas} can be calculated by

$$t_{\text{meas}} = Q(924, t_{\text{set}})/I(924). \quad (10)$$

To solve for the unknowns, $\mathfrak{B}$ and t_{transit} , two different set times must be measured. Data was determined for t_{set} of 5 and 10 s and is shown in Table II. for the measurements made, $\mathfrak{B} = 0.994 \pm 0.06$, so t_{meas} is equal to t_{set} to an accuracy of better than 1%; $t_{\text{ef, tr}}$ was found to be 0.39 ± 0.06 s.

An assumption could be made that for ease of use in the daily performance of the timer check, the program should be stored on a program card or as a "standard" if the unit has these capabilities. Dwell times in such stored programs often increase exponentially over time to compensate for radioactive decay of the source. While this would appear to make evaluating the consistency of the timer easier (assuming that the corrected time should produce a constant reading); however, the correction only applies to the dwell times proper, and not to the effective time due to the transit effect. The daily reading follows the equation

$$R_d = kA_0 e^{-\lambda \tau} (T_s e^{\lambda \tau} + T_t), \quad (11)$$

TABLE IV. Table showing uncertainty in test of K.

Test	Uncertainty in test
Source position	<0.20mm
Dwell time	<0.7%
Source strength consistency	<0.7%

TABLE V. Deviation of K and limits of error for QA measurements.

QA test	$\Delta K < 1\%$	$1\% < \Delta K < 2\%$	$\Delta K > 2\%$
Source positioning	<0.3 mm	$0.3 < x < 0.7$ mm	>0.7 mm
Source strength	<0.05 U_s	$0.05 < A < 0.10$ U_s	>0.10 U_s
Dwell time	<0.1 s	$0.1 < t < 0.2$ s	>0.2 s

where k = a constant, A_0 = the activity at the time of the initial calibration, λ = the decay constant for ^{192}Ir , τ = the time since the initial calibration, T_s = the dwell time specified for the calibration position, and T_t = the time equivalent due to the transit dose. Comparing this daily reading with the reading at the time of the initial calibration, R_0 , gives

$$\begin{aligned} R_d/R_0 &= kA_0 e^{-\lambda \tau} (T_s e^{\lambda \tau} + T_t) / [kA_0 (T_s + T_t)] \\ &= e^{-\lambda \tau} (T_s e^{\lambda \tau} + T_t) / (T_s + T_t) \\ &= (T_s + T_t e^{-\lambda \tau}) / (T_s + T_t). \end{aligned}$$

Were it not for the transit effect, the ratio of daily reading to initial reading would be a constant. Including the transit effect, the ratio varies slowly with time over the life of the source. For a Standard Imaging Model 1000 chamber used with a Nucletron microSelectron, T_t equals approximately 0.4 s. Setting T_s to 10 s results in a 2% change in R_d/R_0 over the life of the source.

As an alternative procedure, programming the unit for a constant dwell time (for example, 10 s) each day yields a ratio

$$\begin{aligned} R_d/R_0 &= kA_0 e^{-\lambda \tau} (T_s + T_t) / [kA_0 (T_s + T_t)], \\ R_d/R_0 &= e^{-\lambda \tau}, \end{aligned}$$

which can be compared to a projection based on a simple calculation.

The values given above establish limits for the QA procedures. These values can be used to set limits for each of the parameters. The points of measurement are labeled A and B as shown in Fig. 3. Point A is taken to be approximately half the maximum (point B).

Over four months in practice, as compared with simultaneous film tests, the device agreed with the film to within a 0.5 mm change in source position. One system always followed the other. At one point, the QA lead insert indicated an erratic change in source position. On investigation, the remote afterloader was found to have a loose optopair, which sent the source to different distances. After repair, the QA tool indicated normal readings.

TABLE VI. Truth table for QA tests, where $\Delta K(x)_A$, $\Delta K(x)_B$ are for current measurements, and $\Delta K(x, t)_B$ is an integrated measurement. On means $\Delta K \leq 1\%$, off means $\Delta K > 1\%$.

Error in item below shows as	Parameter			
	$\Delta K(x)_A$	$\Delta K(x)_B$	$\Delta K(x, t)_B$	$\Delta K(x)_A / \Delta K(x)_B$
Source strength	off	off	off	on
Dwell time	on	on	off	on
Source positioning	off	on	on	off

With familiarity, the QA protocol, using the QA lead insert, was found to take about 5 min. The conventional QA procedure, using radiographic film and a stopwatch, takes 10–15 min and gives positional accuracy to ± 1 mm and a relative dwell-time accuracy of $\pm 5\%$ for a 10 s dwell time. The new QA protocol gives more accurate results, with a significant savings in time. For consistency, no option other than the ionization chamber measurement, seems to exist that provides an adequate accuracy. Certainly, the well chamber approach takes the least time and effort, and provides equivalent or greater information.

A similar analysis can be performed for a QA insert with just one spacer of 4 mm acrylic, as shown in Fig. 1(b). The results are similar, as shown in Table III. The standard deviation for these results is larger. Reviewing film results for these days shows variations of up to 1 mm, which tracks with the QA insert results. This was not noticed on the film until after the fact. Nucletron claims reproducibility on positioning of 0.5 mm.

V. CONCLUSIONS

This methodology has been used for a period of a few months and, as shown in Table IV, found to provide a fast easy way to check source position accuracy to less than 0.4 mm, timer uniformity to less than 2% of set dwell time, and consistency in source calibration to less than 0.3%. Table V

gives action limits and Table VI provides a table for isolating the cause of a problem. These measurements should require approximately 5 min compared with approximately 15 min for the film technique; they can be performed each morning during “warm-up” of the machine.

Timer accuracy, etc. measurements with this technique have an uncertainty of less than 1.5%. This is a margin of a factor of 6 beyond what is needed, so that there is certainty that there is not a recordable event, as defined by the USNRC.⁵

^aPresent address: Radiation Oncology, Bronson Methodist Hospital, 252 East Lovell Street, Kalamazoo, Michigan 49007.

^bPresent address: Radiation Oncology, St. Vincent Hospital, P.O. Box 13508, Green Bay, Wisconsin 54307.

¹S. J. Goetsch, F. H. Attix, D. W. Pearson, and B. R. Thomadsen, “Calibration of Ir-192 high-dose-rate afterloading systems,” *Med. Phys.* **18**, 462–467 (1991).

²S. J. Goetsch, F. H. Attix, L. A. DeWerd, and B. R. Thomadsen, “A new reentrant ionization chamber for the calibration of Iridium-192 high dose rate sources,” *Int. J. Radiat. Oncol. Biol. Phys.* **24**, 167–170 (1992).

³M. B. Podgorsak, L. A. DeWerd, B. R. Thomadsen, and B. R. Paliwal, “Thermal and scatter effects on the radiation sensitivity of well chambers used for high dose rate Ir-192 calibrations,” *Med. Phys.* **19**, 1311–1314 (1992).

⁴M. B. Podgorsak, L. A. DeWerd, and B. R. Paliwal, “The half-life of high dose rate Ir-192 sources,” *Med. Phys.* **20**, 1257–1259 (1993).

⁵U.S. Nuclear Regulatory Commission, Code of Federal Regulations, Title 10, Part 35.2, U.S. Government Printing Office, 1992.