Attenuator Calibration Factors Using High and Low Activity Sources

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Compliance with Nuclear Regulatory Commission regulations pertaining to the range of activities over which linearity of dose calibrators must be tested requires that the procedure be done with two separate sources (one with high activity; the other with low activity) when the attenuator method of checking dose calibrator linearity is used. This may lead to an incorrect judgment of instrument nonlinearity if the same calibration factors are used for both sources. Disparity in calibration factors as high as 6%–9% has been observed. Possible methods for modifying these calibration factors are identified and include: (1) utilizing different factors for high and low sources; (2) modifying the high activity factors by use of established ratios for use with low activity sources; and (3) averaging a series of factors from high activity sources with those from low activity sources.

The test for linearity of a dose calibrator is one of the fundamental quality control measures required by the Nuclear Regulatory Commission (NRC). As stated in 10CFR 35.50, this procedure shall be done "upon installation and at least quarterly thereafter over the range of its use between the highest dosage that will be administered to a patient and 10 microcuries" (*1*).

The accepted method for performing a linearity check on a dose calibrator is time-consuming and cumbersome. It consists of measuring the same source of radionuclide (usually ^{99m}Tc) in the same geometry at specific intervals over a period of days. This series of measurements is then compared to the predicted activity of the source calculated for each of the times at which data were taken by plotting both sets of data on semilog graph paper. To be acceptable, all observed points must be within ± 5% of the calculated activity (*2*).

In recent years, a much simplified method for testing linearity has become available (*3*). This method uses an attenuator kit,* a series of seven tubes (one unlined and six lined with varying thicknesses of lead), which represent the values obtainable at ~0, 6, 12, 20, 30, 40, and 50 hr after initial assay of ^{99m}Tc. The entire test is completed in a matter of minutes, greatly reducing both the time necessary for the procedure and the radiation exposure to the technologist performing the procedure since the source is handled only once.

We recently acquired the attenuator test kit in our nuclear medicine department and prepared to make its use a routine quality assurance (QA) procedure in the laboratory. Since the NRC requires testing of the instrument for all activities used in the department, we determined that the procedure should be performed twice—once using a 100-mCi source and once using a 3.5-mCi source, thereby fulfilling this requirement. To establish the calibration factor for each tube, a series of measurements with the high activity source following the manufacturer's suggested protocol were made. With these factors determined, the two dose calibrators were tested for linearity over the entire range of activities using both the high and the low activity sources.

Unfortunately, both dose calibrators appeared to be nonlinear at activities of <50 μCi. This was a surprise in regard to the older machine because it had been tested for linearity with the conventional method many times and was always found to be perfectly linear. Since the second machine was new and had not yet been put into routine use, it was, therefore, an unknown quantity.

This observation led to a series of experiments to determine: (1) whether or not the equipment was linear; and (2) the reason for the apparent nonlinearity with the attenuator procedure.

MATERIALS AND METHODS

All measurements were made in a CRC-7 dose calibrator†. Sources varied in activity from 3.5 to 110 mCi. A uniform volume of 0.5 ml in a 3-ml syringe or 5 ml in a 10-ml vial was used.

For the decay method, a 110-mCi source was measured at 0, 1, 2, 3, 4, 5, 6, 8, 24, 30, and 48 hr. Activity for each of these times after calibration calculated according to the equa-

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tion for radioactive decay ($A_t = A_0e^{-\lambda t}$) is listed in Table 1. Both the observed and calculated activities were plotted on semilog graph paper.

Using the attenuators, several series of data were recorded, including:

1. Varying the geometry, sources (vial versus syringe), and instrument settings, including background, zero, and ranges.
2. Performing the entire attenuation method each time data for the decay method were taken.
3. Repeating the readings 10 times consecutively at each activity level, ranging from 110 mCi to 3.5 mCi.
4. Measuring paired high (50–100 mCi) and low (3–5 mCi) activity sources for a total of 30 pairs.

RESULTS

Instructions provided with the kit indicate that technical considerations are minimal: (a) place the source in the central tube and measure it in the dose calibrator; (b) record the data; and (c) place each attenuator successively over this central tube and record the data for each. Calculation of attenuation factors is equally simple: divide the activity of the unattenuated source by the activity of each attenuated source. It was difficult to understand what could have been performed improperly; however the procedure was repeated with scrupulous attention given to details such as room background, sampling time, sample volume, and instrument drift. Only two items were of any consequence—sample configuration (indicated in kit instructions) and centering of the tubes in the dose calibrator well (a fault in the design of the tubes). Since the geometric dependence of a gas detector is a well-established phenomenon, neither observation was a surprise. Moreover, each can be easily controlled. Of more importance, our original observation of apparent nonlinearity was again demonstrated.

TABLE 1. Linearity Check of Dose Calibrator Performed Simultaneously by the Conventional Decay Method and by the Attenuator Method Giving Opposing Results

Elapsed time (hr)	Decay Method Activity (mCi) Observed	 Calculated	% Difference
0	110	—	—
6	55.4	55.01	0.7
24	6.77	6.88	1.5
30	3.41	3.44	0.9
48	0.44	0.43	2.3
54	0.213	0.215	1.0
74	0.021	0.021	—
80	0.0106	0.0107	0.7
82	0.0084	0.0085	1.1
86	0.0054	0.0053	1.9

Attenuator Method

Attenuator	Activity (mCi)	Calibration factor	Product
Black	3.41	1.0	3.41
Red (1)	1.98	1.719	3.40
Orange (2)	1.11	3.032	3.36
Yellow (3)	0.307	10.725	3.29
Green (4)	0.131	25.64	3.36
Blue (5)	0.0269	117.68	3.16
Purple (6)	0.0086	330.74	2.84*
			Total 22.82
Mean	3.26		
Upper limit (+5%)	3.42		
Lower limit (−5%)	3.1		

* Not acceptable outside of −5% limit

In order to reaffirm the linearity of the instrument, we then performed the standard method of measuring a source periodically at intervals until essentially total decay. In addition, each time data were taken for the decay curve, the entire attenuator method was performed (Table 1). Both dose calibrators proved to be linear from ~ 100 mCi through 5 μCi by the conventional method. With the attenuator method, however, at activities of 5 mCi and less (unattenuated), both machines occasionally appeared to be nonlinear with the 4th, 5th, and 6th attenuators in place.

These data seemed to indicate that specific calibration factors should be established according to the activity of the source. This observation led to the next set of acquired data: repetition of the procedure 10 times consecutively with the same source. This was done with activities ranging from 110 mCi to 3.5 mCi.

The ten (10) sets of data taken with each source readily demonstrated the reproducibility of the procedure. However, while there was a general increase in the calibration factors with decreasing activity of the source, this increase was not consistent and, therefore, not predictable (Fig. 1).

We finally undertook another series to determine if there was a relationship between the high activity factors and the low activity factors. In addition to calculating the calibration factors for these 30 sets of data, a ratio of high activity factor to low activity factor for all attenuators in each set also was calculated. These ratios proved remarkably consistent with a range of 0.997 ± 0.008 for the first attenuator to 0.940 ± 0.028 for the sixth attenuator (Fig. 2).

This corresponded precisely to the observations made when trying to use the method for the entire range of activities used in the department. The differences observed for the first three attenuators are not sufficient to exceed the allowed 5% variance. With the last three, however, one will observe occasional apparent nonlinearities. For the thickest attenuator, the average difference is 6%, varying from 3% to 9%. It was, in fact, this value which most often proved a problem for use.

DISCUSSION

The cause of this disparity is not clear. Since the geometry of this procedure involves broad-beam conditions, the transmission factor (T) is calculated from the formula:

$$T = Be^{-u}1^{x},$$

where T is transmission factor, B is build-up factor, $^{-u}1$ is linear attenuation coefficient, and x is thickness of the absorber.

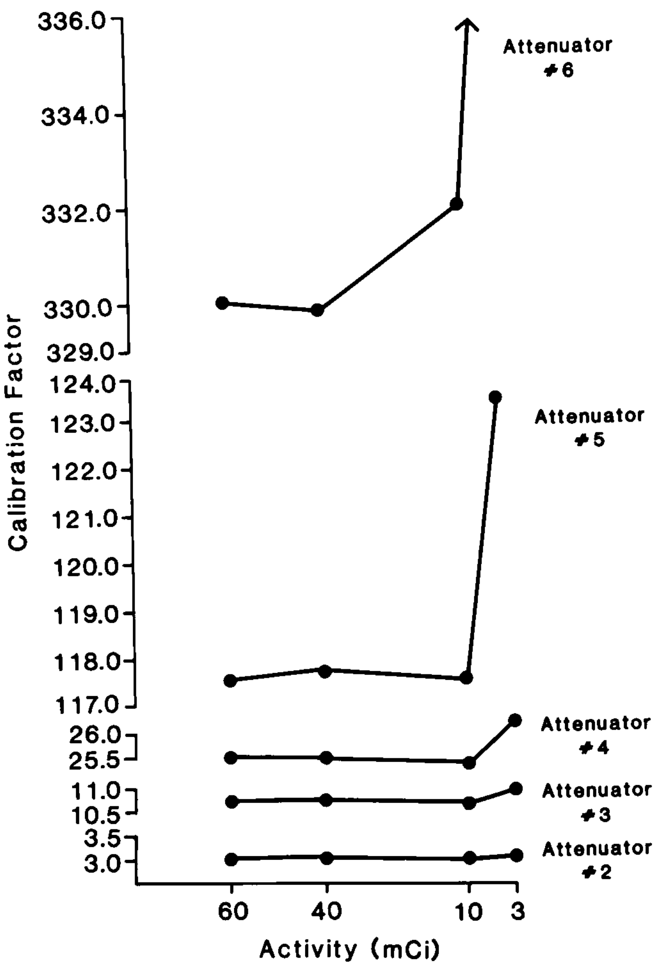

FIG. 1. Relationship of calibration factor to activity of source, expected to remain constant, demonstrates inconsistency of response until activity is <10 mCi, when all factors increase.

Both 'B' and '$^{-u}$1' are dependent on photon energy and composition and thickness of the absorber (*4*). In this procedure, all of these factors are constant. The variable is activity. Therefore, one would predict that the percent attenuation for both sources would be equal. This, in fact, is not so. There is a significant difference in the attenuation of the high and low activity sources.

What exactly is the magnitude of this difference? It is very small in terms of absolute activity but quite significant in terms of percent deviation. The "calibration factors" are reciprocal values of percent of transmission for each attenuator (*3*). Observed calibration factors for the 6th attenuator varied from 328.85–361.68 (difference of 32.83) or percent transmission of 0.00304–0.00276 (difference of 0.00028). This is certainly a significant deviation (i.e., as much as 10% if one compares the difference in the figures to the lower number). However, by the simple mathematical process of "rounding" and using only three significant figures, both figures become 0.003. Can we expect an ionization chamber to be more accurate than this when measuring such small amounts of activity? Actually, the problem is not activity, per se—the machine is quite accurate in measuring unattenuated activity as proven by the decay method (Table 1). It is in the presence of an attenuator that further confuses the poor statistics of low activity and the randomness of radioactive decay that apparent nonlinearities occur.

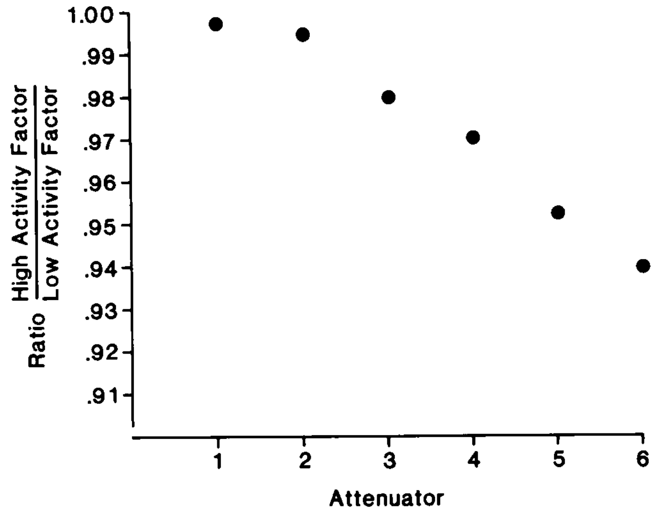

FIG. 2. Ratio of calibration factors for high activity sources to those for low activity sources, expected to be uniform, demonstrates increasing disparity between the factors as attenuator thickness increases.

Since this difference is essentially constant and can be determined, it is possible to adapt the method for routine use in the laboratory. Possible correction methods shown in Table 2 include:

1. Establish separate factors for high and low activity sources. This has the advantage of simplicity and demonstrates the least variation in linearity.
2. Establish factors with a high activity source and correct these for the low activity source by using observed ratios. This is somewhat cumbersome and time-consuming but matches the first method for observed linearity.
3. Calculate a mean of factors from a series of high activity and low activity sources. These mean factors then could be used for all sources. This would be simple to use and the least vulnerable to human error. With these factors, one observes wider variability in results but no false nonlinearities.

Because of constraints imposed by our department's computer program, we have chosen to use option #3, averaging the factors (Table 2). We have found this method reproducible, simple to use, and reliable. Compliance with NRC regulations becomes the easily achievable norm rather than an onerous chore performed haphazardly between patient studies and, sometimes, in spite of a full schedule of patient studies.

Permission to substitute the attenuator method for the longer one will be granted by the NRC if the linearity of the dose calibrator previously has been demonstrated by the method described in the license application (*5*). A sample form for filing a license amendment application is provided in the manufacturer's instruction manual (*5*). However, one should be aware of potential pitfalls before instituting this method.

TABLE 2. Calculation of Linearity Using Suggested Correction Methods

Method A

Factors—Average high for high activity

Attenuator	Activity (mCi)	Calibration factor	Product
Black	85.9	1.0	85.9
Red (1)	50.0	1.719	85.95
Orange (2)	28.3	3.032	85.8
Yellow (3)	8.04	10.725	86.2
Green (4)	3.36	25.64	86.1
Blue (5)	0.73	117.68	85.9
Purple (6)	0.26	330.74	86.0
			Total 601.85
Mean	85.98		
Upper limit (+5%)	90.28		
Lower limit (−5%)	81.68		

Average low for for low activity

Attenuator	Activity	Calibration factor	Product
Black	3.33	1.0	3.33
Red (1)	1.94	1.729	3.35
Orange (2)	1.09	3.054	3.33
Yellow (3)	0.306	10.949	3.35
Green (4)	0.126	26.384	3.32
Blue (5)	0.027	123.45	3.33
Purple (6)	0.0093	358.519	3.33
			Total 23.34
Mean	3.32		
Upper limit (+5%)	3.51		
Lower limit (−5%)	3.17		

Method B

Factors—Average high for high activity

Attenuator	Activity (mCi)	Calibration factor	Product
Black	85.9	1.0	85.9
Red (1)	50.0	1.719	85.95
Orange (2)	28.3	3.032	85.8
Yellow (3)	8.04	10.725	86.2
Green (4)	3.36	25.64	86.1
Blue (5)	0.73	117.68	85.9
Purple (6)	0.26	330.74	86.0
			Total 601.85
Mean	85.98		
Upper limit (+5%)	90.28		
Lower limit (−5%)	81.68		

Average high for low activity ratio

Attenuator	Activity	Calibration factor	Product
Black	3.33	1.0	3.33
Red (1)	1.94	1.724	3.34
Orange (2)	1.09	3.05	3.32
Yellow (3)	0.306	11.04	3.38
Green (4)	0.126	26.4	3.33
Green (5)	0.027	123.61	3.34
Purple (6)	0.0093	352.22	3.28
			Total 23.32
Mean	3.33		
Upper limit (+5%)	3.498		
Lower limit (−5%)	3.16		

Method C

Factors—Mean average high and low

Attenuator	Activity	Calibration factor	Product
Black	85.9	1.0	85.9
Red (1)	50.0	1.721	86.05
Orange (2)	28.3	3.043	86.12
Yellow (3)	8.04	10.837	87.13
Green (4)	3.36	26.01	87.39
Blue (5)	0.73	120.565	88.01
Purple (6)	0.26	344.629	89.6
			Total 610.20
Mean	87.17		
Upper limit (+5%)	91.53		
Lower limit (−5%)	82.8		

Attenuator	Activity (mCi)	Calibration factor	Product
Black	3.33	1.0	3.33
Red (1)	1.94	1.721	3.34
Orange (2)	1.09	3.043	3.32
Yellow (3)	0.306	10.837	3.32
Green (4)	0.126	26.01	3.28
Blue (5)	0.027	120.565	3.26
Purple (6)	0.0093	344.629	3.21
			Total 23.06
Mean	3.29		
Upper limit (+5%)	3.46		
Lower limit (−5%)	3.13		

CONCLUSION

A modified method of calculating calibration factors for use with the attenuator method of determining linearity of dose calibrators has been presented. With this modification, the method can be used with confidence, thereby reducing the time required for this QA procedure and the radiation exposure to the technologist performing the task.

NOTES

*Calicheck, Calcorp, Inc., Cleveland, OH

†CRC-7 dose calibrator, Capintec Inc., Ramsey, NJ

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