Comparison of Attenuators for Linearity Testing of The Dose Calibrator

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The performance of two commercially available attenuator devices used for dose calibrator linearity testing are evaluated. Although both devices function adequately, the use of the manufacturers' recommended instructions may result in test results that misrepresent the dose calibrator's performance. Recommendations for proper use of the attenuator devices are presented as well as a step by step protocol.

Quality assurance testing in nuclear medicine includes the periodic testing of the dose calibrator. The Nuclear Regulatory Commission (NRC) requires four standard tests to be performed: constancy (daily), linearity (at installation and quarterly), accuracy (at installation and annually), and geometry (at installation) (*1,2*).

In order to determine if the dose calibrator response is truly linear, linearity testing must be performed over a range of activities from 10 μCi to the highest dose administered to a patient (up to 200 mCi therapy doses in our clinic) with an acceptable deviation of not more than 10% from a "best fit" straight line (*1*). The NRC Regulatory Guide 10.8, however, suggests that this tolerance be reduced to 5% (*2*).

The most commonly used method for performing a linearity test is the decay method utilizing the radionuclide technetium-99m (^{99m}Tc) (*2*), requiring numerous readings over an extended time period (Table 1). Alternately, a series of attenuators of varying thickness may be used to simulate decay (Figs. 1-2) (*2-5*). Calibration factors, specific to each dose calibrator used, must be determined for each attenuator after it has been demonstrated that the dose calibrator responds linearly by the decay method.

The purpose of this study is to evaluate the performance of two commercially available attenuator devices*†.

MATERIALS AND METHODS

The measurements for the three linearity test procedures were performed using 20 ml evacuated vials filled with 20 ml [^{99m}Tc]sodium pertechnetate in solution. Molybdenum-99 content was 2.13×10^{-4} μCi/mCi. Placement of the vial for measurement in each procedure as well as alignment of the attenuators was consistent in order to eliminate errors from differing geometry. The dose calibrator ‡ was properly zeroed before each measurement. Dose calibrator constancy was tested daily, and geometry and accuracy had been performed during the prior three months.

TABLE 1. Linearity Testing by Decay Method

Time	Activity (mCi)	% Deviation*
0	225	+1.46
6	111.3	+0.03
24	14	-0.38
30	7.01	-0.58
48	0.878	-1.41
54	0.437	-2.19
72	0.0557	-1.29
78	0.0285	+0.66
96	0.0037	+3.47

*Percent deviation from "best fit" straight line $y = 221.77e^{-0.11495t}$ (see text).

Decay Method. Measurements were obtained at intervals from 0 to 96 hr with a range of activity from 225 mCi to 3.7 μCi, respectively (Table 1). Least squares analysis was performed on a logarithmic transform of the data to determine the "best fit" straight line (*1*) whose slope equals the decay constant of ^{99m}Tc.

Attenuator A* (Fig. 1). Measurements of activity were made using six colored tubes (red, orange, yellow, green, blue, and purple) of varying lead thickness. A central base tube for each measurement maintained consistent geometry of the source. Simulated activity of the source ranged from 217 mCi to 9.8μCi (Table 2). Each colored tube was inserted over the central base tube, and the measurement of activity was then recorded as

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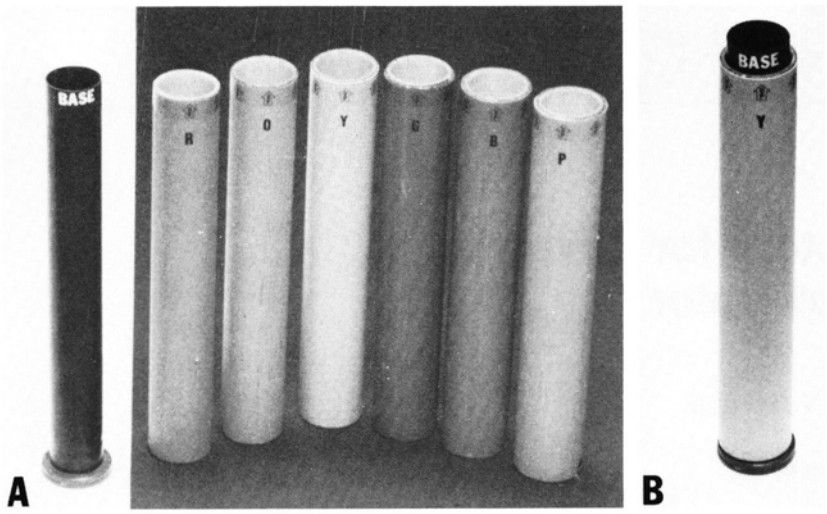

FIG. 1. (A) The components of attenuator A* are pictured with the base on the left and the six colored tubes to the right in order of increasing attenuation. R=red, O=orange, Y=yellow, G=green, B=blue, P=purple. (B) The base and yellow tubes are positioned for attenuation.

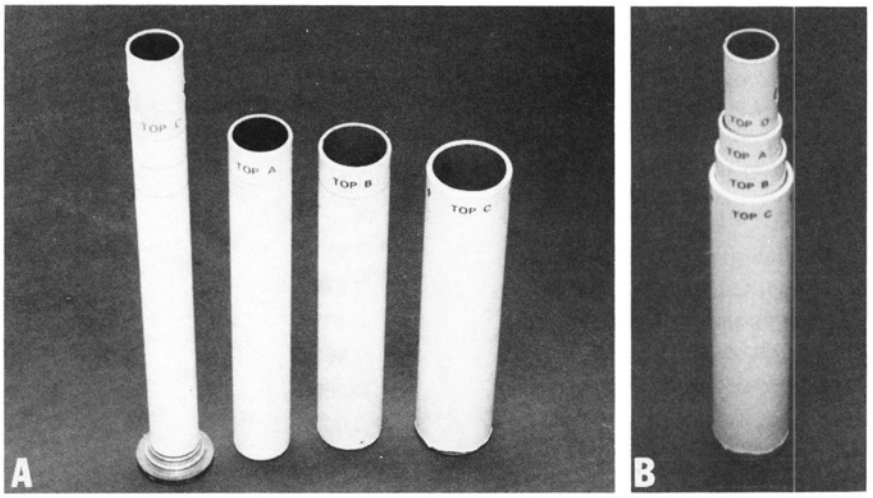

FIG. 2. (A) The components of attenuator B† are pictured with the base on the left and the three lettered tubes to the right in order of increasing attenuation. O=Base. (B) The base tube and tubes A,B, and C are positioned for maximum attenuation.

described by the manufacturer (*4*).

***Attenuator B†* (*Fig. 2*).** Activity measurements were made with three tubes labeled A, B, and C of different lead thickness. The central base tube maintained consistent geometry of the source. Simulated activity of the source ranged from 213 mCi to 9.1 μCi (Table 3). Each letter designated tube was inserted over the central tube separately and in combination with each other, and a measurement of activity was then recorded as described by the manufacturer (*5*).

Subsequent to determining that the dose calibrator in fact was performing linearly with a tolerance of 5% (*2*), the measurements using either of the attenuator sets A or B were acquired within a three-minute period. These data were duplicated and averaged to reduce experimental error, and calibration factors for each attenuator set (A and B) were calculated by dividing the base dose calibrator reading by itself and by each subsequent reading (Tables 2 and 3).

RESULTS

Decay Method. The dose calibrator was found to be performing linearly over the required 200 mCi to 10 μCi range of activity (Table 1). Although all results were within the suggested 5% deviation from the "best fit" straight line, the greatest deviation was consistently at the lowest activity level.

Attenuator A. In order to present the dose calibrator with the required range of simulated activity, the test had to be performed with two different doses (213 mCi and 3.33 mCi in this experiment). The calibration factors derived from the high and low dose data were all within 0.97% of one another (Table 2).

Attenuator B. As with attenuator A, two different doses needed to be used (211 mCi and 6.19 mCi in this experiment). The calibration factors derived from the two doses were all within 0.81% of one another (Table 3).

DISCUSSION

Linearity testing of the dose calibrator is an important and mandated procedure, which should be performed upon installation and at least quarterly (*1*). Although the importance of this test is well documented, compliance with the requirement to perform linearity testing has not been adequate. A survey of hospitals of varying bed size showed an overall test noncompliance rate of 63.3% (*4*). Noncompliance among the

TABLE 2. Attenuator A: Measurement of Simulated Activity

Tube	Average Activity (mCi)	Calibration Factor*
Base	213	1
Red	115.35	1.8466
Orange	61.55	3.4606
Yellow	16.20	13.148
Green	4.53	47.020
Blue	1.348	158.01
Purple	0.602	353.82
Base	3.33	1
Red	1.79	1.8603
Orange	0.953	3.4942
Yellow	0.2535	13.136
Green	0.07025	47.402
Blue	0.0212	157.08
Purple	0.00945	352.38

*Calibration factor is determined by dividing the base measurement by itself and each subsequent reading.

TABLE 3. Attenuator B: Measurement of Simulated Activity

Tube	Average Activity (mCi)	Calibration Factor*
Base	211	1
A	55.55	3.7984
B	35.5	5.9437
AB	9.535	22.129
C	6.065	34.790
AC	1.675	125.97
BC	1.076	196.10
ABC	0.3005	702.16
Base	6.19	1
A	1.625	3.8092
B	1.036	5.9749
AB	0.279	22.186
C	0.1765	35.071
AC	0.0488	126.84
BC	0.03135	197.45
ABC	0.0088	703.41

*Calibration factor is determined by dividing the base measurement by itself and each subsequent reading.

states surveyed was as low as 4.5% and as high as 100% (*6*). This degree of noncompliance is unacceptable and may be due in part to the expense of purchasing and/or utilizing a large source of activity that cannot be used for patients, and/or the time required (96 hr) to complete the linearity test by the decay method. Attenuators provide a simple and rapid method for measuring a full range of activity in a brief period of time (3 min). Subsequent to the test, the source may be used clinically.

The manufacturers of both commercially available attenuator devices recommend that initially the dose calibrator linearity should be determined by "standard" means (decay or dilution) (*4–5*) (i.e., no measurement more than 5% from the "best fit" straight line (*2*)). This implies that any point may deviate up to 5% from perfect linearity when the calibrator is considered "linear." From this, then, the calculted calibration factors may contain as much as 5% nonlinearity. The recommendations of both manufacturers (*4–5*) err in assuming at this point that the calibrator is now perfectly linear and that there is no error in the calculated calibration factors. It then follows that a subsequent 5% deviation from the calculated calibration factors may result in as much as 10% nonlinearity (Fig. 3). Similarly, a 10% deviation from the calculated calibration factors could result in only 5% (acceptable) nonlinearity (Fig. 3). For these reasons, we make the following two changes in the attenuator manufacturers' recommendations:

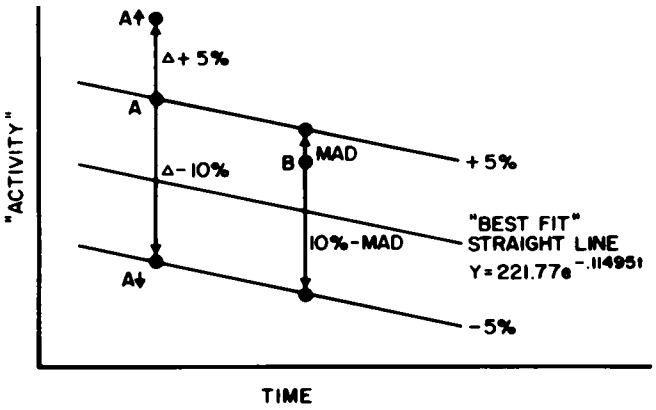

FIG. 3. The graph represents the "best fit" straight line ± the allowable 5% deviation within which, if all points reside, a dose calibrator is considered linear (by the decay method). Point A represents a point that is within 5% of the "line" and therefore does not make the test "nonlinear", although it does represent 5% nonlinearity. A subsequent +5% variance increase in attenuator testing may result in an unacceptable 10% nonlinearity (point A↑). Similarly, a subsequent −10% variance decrease may result in an acceptable 5% nonlinearity (point A↓). Point B represents the maximum nonlinearity that occurred in a decay linearity test (+3.5% in our experiment. Maximum allowable deviation (MAD) is the maximum deviation allowed in a subsequent attenuator test, that will assure that there is no more than 5% nonlinearity (1.5% in our experiment). If 10% − MAD is exceeded, then the calibrator is surely nonlinear (8.5% in our experiment). If the attenuator test > MAD and ≤10% − MAD (between 1.5% and 8.5% in our experiment), then a retest by the decay method is indicated.

1. From the data recorded during initial linearity testing by "standard" means (decay or dilution), the maximum percent deviation of any point from the "best fit" straight line is recorded. This percent is subtracted from 5% (or 10% if a more lenient test is used), and the difference is the maximum allowable deviation (MAD) of the calculated calibration factors.
2. If subsequent calibration factors exceed MAD by less than 10% − MAD (20% − MAD if the more lenient test is used), a linearity retest by "standard" means should be performed. If the 10% − MAD is exceeded, it can be assumed that the calibrator is nonlinear (see Appendix). In our experiment, MAD = only 1.53% mainly because of the poorer calibrator linearity at the 3.7 μCi acitivty range.

A majority of nuclear medicine services will require at least two sets of measurements in order to comply with NRC requirements. As seen in Tables 2 and 3, neither attenuator covers the range from the largest activity administered to patients to 10 μCi. Thus, a service which potentially doses patients with 150 mCi therapy doses would require a set of measurements encompassing this high activity and a set of measurements starting at approximately 2.9 mCi and 6.5 mCi for attenuators A and B, respectively. Even services that administer no more than 30 mCi would still require two sets of measurements.

Both attenuators were found to adequately perform the linearity test, and one can not be recommended over the other. Considerations for any nuclear medicine services desiring to obtain an attenuator are the best negotiable price and the difference in outside diameters of the attenuators. Attenuators A and B had measured outside diameters of 4.8 cm and 6.1 cm, respectively. This diameter difference may influence the purchase of one attenuator over the other, depending upon the inside diameter of the dose calibrator well in use.

The use of commercially available attenuators for linearity testing is a simple and rapid procedure. These attenuators provide compliance with regulatory requirements, ensure proper functioning of dose calibrators, reduce exposure to personnel, and are an important aspect of any well conducted nuclear medicine quality assurance program.

If the procedure described by each manufacturer is followed exactly, a source of systematic error may give test results which are not truly indicative of the dose calibrator's performance. Adherence to the modifications suggested in this paper reduces these errors considerably.

NOTES

*Calicheck, Calcorp Inc., Cleveland, OH
†Lineator, Atomic Products Corp, Center Moriches, NY
‡Capintec Model CRC-30, Capintec Inc., Mt. Vernon, NY

APPENDIX

This appendix serves as an aid and example to help one perform linearity testing of the dose calibrator using either the the attenuator method or decay method.

ATTENUATOR TABLE

Tube	Activity (mCi) (A)	Present Factor (B)	Initial Factor (C)	% Ratio (D)	% Deviation (E)
Base	212	1	1	100	+0.1
A	56.2	3.7722	3.7984	99.31	−0.6
B	36.1	5.8726	5.9437	98.80	−1.1
AB	9.54	22.222	22.129	100.42	+0.5
C	6.10	34.754	34.790	99.90	0
AC	1.63	130.06	125.97	103.24	+3.4
BC	1.11	190.99	196.10	97.39	−2.5
ABC	0.302	701.99	702.16	99.98	+0.1
				Mean 99.88	
Base	6.22	1	1	100	
A	1.64	3.7927	3.8092	99.57	−0.2
B	1.041	5.9750	5.9749	100.00	+0.3
AB	0.276	22.536	22.186	101.58	+1.8
C	0.182	34.176	35.071	97.45	−2.3
AC	0.0489	127.20	126.84	100.38	+0.6
BC	0.0316	196.84	197.45	99.67	−0.1
ABC	0.089	698.88	703.41	99.36	−0.4
				Mean 99.75	

Notes: Values in column (B) = $\frac{\text{base reading in column (A)}}{\text{activity in column (A)}}$.

Values in column (C) are initial test factors (see Table 3).

Column (D) = $\frac{\text{column (B) values}}{\text{column (C) values}} \times 100$,

then calculate mean column (D).

Column (E) = $\left(\frac{\text{column (D) values}}{\text{mean column (D)}} - 1\right) \times 100$.

If the largest absolute value from column (E) is:
1. ≤ MAD, test is complete and calibrator is linear.
2. > MAD and ≤ 10% − MAD, then redo decay method to determine if calibrator is linear.
3. > 10% − MAD, then calibrator is not linear.

In this example, four results exceed MAD (1.5%) but none exceed 10% − MAD (8.5%). Therefore, a retest by the decay method is in order. If a more lenient test (±10%) were used, however, the calibrator would be considered linear (MAD = 6.5%, 20% − MAD = 13.5%).

DECAY TABLE

Time (Hrs)	Activity (mCi) (A)	Expected Activity (mCi) (B)	% Ratio (C)	% Deviation (D)
0	225.0	225.0	100	+1.5
6	111.3	112.9	98.58	0
24	14.0	14.26	98.18	−0.4
30	7.01	7.154	97.99	−0.6
48	0.878	0.9035	97.18	−1.4
54	0.437	0.4533	96.40	−2.2
72	0.0557	0.05725	97.29	−1.3
78	0.0285	0.02872	99.23	+0.7
96	0.0037	0.003627	102.01	+3.5
			Mean 98.54	MAD 1.5%
				10% − MAD 8.5%

Notes: Values in column (B) = the initial reading in Column (A) decayed for time ($T_{½}$ = 6.03 hr).

$$\text{Column (C)} = \frac{\text{column (A) values}}{\text{column (B) values}} \times 100,$$

then calculate mean column (C).

$$\text{Column (D)} = \left(\frac{\text{column (C) values}}{\text{mean column (C)}} - 1\right) \times 100.$$

MAD = 5% the absolute value of the largest absolute value from column (D).

Performance of decay method and initial calibration factors should be determined when calibrator is most linear (at installation) in order to maximize MAD.

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