Quality Control Testing of Dose Calibrators

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We have reviewed quality control testing of dose calibrators and have analyzed the potential for error. The uncertainty in half-lives of reference sources can lead to inaccurate assessment of the accuracy and constancy in dose calibrator performance. Molybdenum-99 contamination of ^{99m}Tc used as a reference source can appear as a nonlinear response of the dose calibrator. The useful life of a reference source and the tolerable amount of ^{99}Mo contamination are examined.
Key Words: dose calibrator; accuracy; constancy; linearity; geometry; quality control

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The assay of radiopharmaceuticals for the amount of radioactivity is a well-established practice that generally is required prior to their clinical use. The radionuclide dose calibrator, a pressurized re-entrant ion chamber, is most commonly used for this purpose. Its basic theories of operation remain largely unchanged from that described by Suzuki, et al. (*1*) in 1976. The technology and the regulations for quality control testing of this instrument, however, have been evolving continuously over the past two decades.

Radioactive material licensing agencies require periodic quality control testing for accuracy, linearity, constancy and geometry dependence of dose calibrators (*2*). Suggested testing procedures and methods of analysis are found in the Nuclear Regulatory Commission (NRC) Regulatory Guide 10.8 (*3*). Commercially available data analysis programs are in widespread use for this purpose. Spreadsheet type computer software can also be customized for this purpose (*4*).

Accepted methods of testing most often assume ideal testing conditions and neglect to declare the limitation of the testing conditions. A suboptimal testing condition could mislead one to believe that the instrument was responding in violation of regulatory limits. This in turn could lead to unnecessary repair and delay in patient care.

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Examples of such confounders will be presented in this paper. They are: the inaccuracy in the certified value of reference sources; uncertainties of half-lives; incomplete accounting in sample preparation; ^{99}Mo contamination of ^{99m}Tc; and insufficient rigor in data analysis.

ACCURACY

A reference source with a certified activity $A_c \pm \delta A_c$ is assayed by the dose calibrator and the result is compared to the activity, A, of the standard at the time of measurement. Let us first suppose that δA_c is negligible; then the activity can be computed from the certified value and the half-life of the radioisotope. An inaccuracy of the half-life introduces an error, δA_d, to the derived value in the following manner:

$$\frac{\delta A_d}{A_d} = \lambda t \frac{\delta T_{1/2}}{T_{1/2}} \qquad \text{Eq. 1}$$

where $T_{1/2}$ is the half-life, $\delta T_{1/2}$ is the associated uncertainty, and A_d is the decay-corrected activity. The decay constant, λ, equals $\ln 2/T_{1/2}$. In other words, the uncertainty of the computed activity increases with the age of the reference source and at the rate of relative or percent error of the half-life (i.e., $\delta T_{1/2}/T_{1/2}$).

Radionuclides most commonly used as reference sources include ^{57}Co, ^{137}Cs and ^{133}Ba (Table 1). The reported physical half-life of ^{57}Co has a range of 0.3% and an uncertainty of

TABLE 1
Half-lives of Reference Sources*

Reference	^{57}Co	^{133}Ba	^{137}Cs
Shleien (*19*)	270.9 ± ?d		30.17 ± ?y
NCRP 58 (*20*)	271.7 ± 0.2d (±0.07%)	10.5 ± 0.1y (±0.95%)	30.0 ± 0.2y (±0.67%)
Tuli (*5*)	271.80 ± 0.05d (±0.02%)	10.52 ± 0.13y (±1.24%)	30.1 ± 0.2y (±0.66%)
MIRD (*21*)	271 ± ?d	10.4 ± ?y	30.0 ± ?y

*Uncertainties are quoted in absolute values as well as in percentages. A question mark is used to indicate where the uncertainty has not been given.

0.02% to 0.07%, while ^{137}Cs has a range of 0.56% and an uncertainty of 0.66% to 0.67%, and the half-life of ^{133}Ba has a range of 1.15% and an uncertainty of 0.95% to 1.24%. The half-life of ^{133}Ba appears to be the least well known. If a quantity of ^{133}Ba initially has been calibrated precisely and if an error of 1% is made in the value of its half-life, the activity is known only to within 0.7% and 1.4% after one half-life and two half-lives, respectively.

It is not unusual for reference sources to remain in use after several half-lives. To determine when a reference source should be replaced, we can rearrange Equation 1 as follows:

$$T_r = \frac{T_{1/2}}{\ln 2} \times \frac{\delta A_d / A_d}{\delta T_{1/2} / T_{1/2}} \qquad \text{Eq. 2}$$

The age at replacement, or the useful life, is directly proportional to the ratio of the relative uncertainty in the computed activity to the relative uncertainty in the value of the half-life. For example, if we are willing to accept 1% uncertainty in the activity, the useful life will be 14.4 half-lives for 0.1% error and 1.44 half-lives for 1.0% error in $\delta T_{1/2}/T_{1/2}$. The half-life of ^{57}Co is known to be better than 0.1% and typically this reference source decays to its minimum permissible activity before the error in the computed activity becomes unacceptable (it takes less than 7 half-lives to decay from 237 MBq to 1.9 MBq or 6.4 mCi to 50 μCi). The half-life of ^{137}Cs is known to about 0.7%, the useful life is estimated to be 2 half-lives or 60 yr. For ^{133}Ba, an error of 0.3% to 2% can be made in the value of the half-life. The corresponding useful life is 4.8 to 0.72 half-lives or 50 yr to 7.6 yr. If the tolerable error in computed activity is increased from 1% to 2%, then the useful life is lengthened by a factor of two. The NRC requires the use of at least two different radioisotopes for calibration (*2*). Cobalt-57 and ^{137}Cs are the preferred reference sources when the useful life of ^{133}Ba is as short as 7.6 yr.

When δA_c is not negligible, the uncertainty of the true activity, A, of the reference source at the time of dose calibrator testing has two components: the error δA_c of the certified value A_c as well as the error δA_d introduced by the decay computation. If these errors are independent, then the total error, δA, is:

$$\left(\frac{\delta A}{A}\right)^2 = \left(\frac{\delta A_c}{A_c}\right)^2 + \left(\frac{\delta A_d}{A_d}\right)^2 \qquad \text{Eq. 3}$$

The NRC requires reference sources to be calibrated to better than 5% uncertainty (*2*). This condition is interpreted to be applicable at the date of calibration. That is, the upper limit on the first term ($\delta A_c/A_c$) in Equation 3 is 5%. The National Institute of Standards and Technology can either provide sources for nuclear medicine quality control or calibrate sources most frequently used in nuclear medicine. These sources are generally calibrated to better than 2%. Radiopharmaceutical companies provide secondary standards at lower cost and generally certify the calibrated values to 5% or less. These uncertainties are usually quoted at 90% confidence level or at three standard deviations. That is, the stated value is very unlikely to deviate from the true value by the quoted uncertainty. However, if a reference source has a stated value that differs almost 5% from its true activity, and the discrepancy is enlarged by the uncertainty in decay computation, then a measurement by an ideal dose calibrator can still differ from the computed activity by more than the NRC's recommended action level of 5% (*3*).

TABLE 2
Suggested Courses of Action in Accuracy Testing Using Two Reference Sources

Source A	Source B	Recommended action
<5%	<5%	None
<5%	>5%, <10%	Examine source B
>5%, <10%	<5%	Examine source A
>5%, <10%	>5%, <10%	Examine sources
<5%	>10%	Contact manufacturer
>10%	<5%	Contact manufacturer
>5%, <10%	>10%	Contact manufacturer
>10%	>5%, <10%	Contact manufacturer
>10%	>10%	Contact manufacturer

Another conflict, with the NRC's specification for reference sources and action level, is our reasonable expectation of current technology. A manufacturer of dose calibrators has a stated uncertainty for the assay of particular isotopes. Sometimes this uncertainty is a combination of equipment specifications, but generally it can be considered to be 3% nominally. Subtracting this from the value of action level will leave only 2% margin for error in the stated or derived activity of a reference source, whereas the calibration of the source might have fully exploited the 5% tolerance allowed by the NRC. For example, a 3.70 MBq (100 μCi) ^{137}Cs reference source has been certified to be 3.52 MBq (95 μCi) (i.e., an error of −5%). An assay by a dose calibrator shows 3.81 MBq (103 μCi) (i.e., high by +3%). This differs from the certified value by +8.4%. Both the calibrator and the source are within the stated specifications and yet the "inaccuracy", as defined, exceeds the action level.

When the activity of a reference source is certified at a high confidence level, the inaccuracy displayed in its assay with a dose calibrator should rarely exceed the NRC action level of 5%, and certainly should not exceed the limit of 10%. The NRC action level of 5% does not require repair or replacement of the dose calibrator unless this has been so stated as a licensing condition. The limit of 10% does require the repair or replacement of dose calibrators.

For an accuracy test using two reference sources of different radioisotopes we suggest the following course of action (Table 2). If a test with one of the reference sources exceeds the action level but complies with the limit of 10%, then the source is suspect. The test should be repeated with another reference source of the same radioisotope. The local nuclear pharmacy might be able to assist with the examination of any questionable reference source. If the tests of both reference sources exceed the action level but comply with the limit of 10%, the probability of a drift in the dose calibrator is higher than the

probability of having gross inaccuracies in the certified values of both sources. Nevertheless, it is less disruptive to the clinic to first examine the sources, or try different sources, before sending the calibrator out for adjustment. If one or both of the sources exceed the limit of 10%, then the calibrator should not be used until the problem has been resolved.

Necessity for accuracy testing has been illustrated by the finding of errors greater than 15% in surveys conducted more than 20 yr ago (*6–8*). With much improved current technology, dose calibrators are expected to be more accurate. However, the uncertainties in the certified values and half-lives of reference sources are placing a limit on the accuracy test.

GEOMETRY

A dose calibrator's response may depend on the placement of a radioactive source, its volume and the characteristics of the container. Such geometry dependence should be determined over the range of volumes and volume configurations for which the dose calibrator will be used (*2*). The NRC Regulatory Guide prescribes the use of dilution to determine the volume dependence in a 3-cc syringe and the volume dependence in a vial (*3*). However, this prescription should be complemented by determination of the correlation between the instrument's response to a syringe (with caution on the handling of the needle) and to a vial.

It is very likely that a vial of radiopharmaceutical is assayed at the same geometrical location as a reference source in an accuracy test. When a syringe is used, it is usually placed at a very different location in the dose calibrator. The correction factor for this geometry dependence can be determined by assaying a vial before and after a withdrawal of ^{99m}Tc solution. The difference is compared to the assay of the withdrawn sample in the syringe. The needle used to withdraw or transfer a small volume of radioactive solution can contain more than 1% of the total activity. This is a significant amount when NRC is recommending an action level of 5% (*3*). Therefore, this amount should not be lost unintentionally when withdrawing nonradioactive liquid to increase volume in the syringe.

Geometry dependence was among the results of surveys published in 1974 (*7,8*). A more recent study by Hooper and Davies (*9*) showed as much as 9% dependence on the vertical position and 5% dependence on lateral position. Therefore, the sample holder should be used consistently in the geometry dependence test and the assay of radiopharmaceuticals.

CONSTANCY

Relatively long-lived sources are used daily to check the consistency of performance of frequently used settings. The uncertainties in the half-life of the check sources as discussed in accuracy testing have less effect here. Constancy test is a relative comparison between measurements made over a period shorter than a half-life of the check source. However, this does not mean comparing two contiguous measurements. If the dose calibrator drifts in a biased manner by an amount less the NRC-recommended action level of 5% (*3*) in several days, in a few months the total deviation could be excessive. The results of testing should be compared to values obtained when the dose calibrator's performance was found to be acceptable.

Most people have been using values from acceptance testing and the half-life of the dedicated check source to predict the desired value at the date of constancy testing (*3,4,10*). An alternate to this comparison of absolute values would be to use the ratios of readings at different settings with the same check source in the dose calibrator at acceptance testing as reference values. These relative values should be independent of the half-life of the check source and the associated uncertainty. Correction for decay is unnecessary and, therefore, the analysis of constancy test is simplified.

LINEARITY

The licensee is required by the NRC to test the response of a dose calibrator over the range of its use, between the highest dosage that will be administered to a patient and a lower limit in kBq (μCi) (*2*). This limit has recently been revised from 370 kBq to 1.1 MBq (10 μCi to 30 μCi). The highest dosage most likely comes from the therapeutic administration of ^{131}I. Technetium-99m, with its much shorter half-life and much lower energy, is more suitable technically and is safer for the linearity testing of dose calibrators. Therefore, an amount of ^{99m}Tc simulating the largest amount of ^{131}I used should be assayed. Oswald, et al. (*11*) and Hung, et al. (*12*) determined that approximately 52.9 MBq (1.43 mCi) of ^{99m}Tc would elicit the same response as 37.0 MBq (1 mCi) of ^{131}I. This equivalency is not expected to be the same for all dose calibrators. The user of a dose calibrator can determine his own value by placing a radioactive source in the dose and calibrator and comparing the readings at the ^{99m}Tc and the ^{131}I settings.

The two methods generally used in linearity testing have been described in the NRC Regulatory Guide (*3*): decay method and shield method. The principles have been described in this guide as well as in other available literature. However, there is insufficient explicit emphasis on meticulous attention required in sample preparation, measurement and analysis.

LINEARITY-DECAY METHOD

A sample of ^{99m}Tc is assayed continuously. One of the methods of analysis described in the NRC Regulatory Guide (*3*) consists of plotting the assay results versus time on a semilogarithmic graph, drawing a best-fit straight line and finding the largest deviation of a data point from the line. We found the thickness of the hand-drawn line took up much of the 5% tolerance, an action level recommended by the NRC Regulatory Guide (*3*). Therefore, the manual graphical method of measuring deviation is somewhat inaccurate.

The other method is to use a table for a comparison of the assay results with the expected values. If one uses the initial measurement and predicts the "correct" values for the subsequent assays (*4*), there is the potential of overestimating the deviation or nonlinearity. An improvement would be to use data at mid-interval and compute other values by exponential decay. However, there is no reason to believe this point at

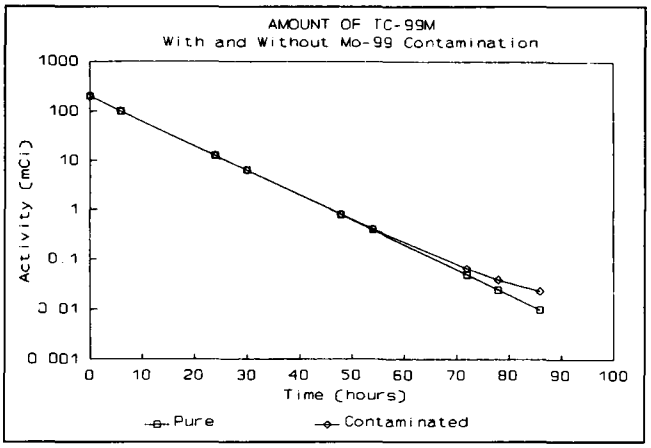

FIGURE 1. Comparison of ^{99m}Tc time-activity curves from a pure initial dose and a dose contaminated with 30 μCi of ^{99}Mo.

mid-interval is more accurate than others to be used for extrapolation. An improvement would be to fit a straight line to the logarithmic transform of data with the known decay constant as the slope (*13*).

The half-life value for ^{99m}Tc found in literature has a range of ±0.03 hr and could lead to an inaccuracy of as much as 2% in nonlinearity when the assay results are compared with expected values (*14*). This discrepancy is appreciable when compared to the action level of 5% recommended by NRC (*3*). This situation is ameliorated if we use the most recent and precise determination of the half-life, 6.007 ± 0.002 hr (*15*).

The decay method as described above assumes a pure sample of ^{99m}Tc. Suppose we start with 7.40 GBq (200 mCi) of ^{99m}Tc, containing the maximum concentration of ^{99}Mo allowed by law for the radiopharmaceutical (10CFR35§204). This amounts to 1.1 MBq (30 μCi) of impurity. This has no measurable effect on the initial assay of the sample. As the ^{99m}Tc decays, however, the ^{99}Mo, having a longer half-life of 65.94 hr, becomes appreciable (Fig. 1). For example, at 78 hr, there will be 914 kBq (24.7 μCi) of ^{99m}Tc left and there will still be 488 kBq (13.2 μCi) of ^{99}Mo. The decaying ^{99}Mo would have generated an additional 537 kBq (14.5 μCi) of ^{99m}Tc, which represents a 59% deviation from the ideal value. Radiation from the ^{99}Mo will also be emulating an additional amount of ^{99m}Tc. From the known sensitivities of a particular dose calibrator, the total amount of activity recorded is estimated to be about 2.19 MBq (59.1 μCi) instead of the predicted value of 914 kBq (24.7 μCi). This represents 239% deviation from linearity. In this example, the tolerable amount of ^{99}Mo contamination would be less than 148 kBq (4 μCi) in 7.40 GBq (200 mCi) of ^{99m}Tc.

LINEARITY-SHIELD METHOD

The decay method requires several days to cover the range of activity required. To eliminate the waiting period between successive measurements, shields or attenuators were introduced to simulate the decay of ^{99m}Tc by reducing the radiation from the sample to the dose calibrator (*16*). When using the commercially available shields, most departments need a large activity sample (>7.40 GBq or 200 mCi) and a small activity sample (111–222 MBq or 3–6 mCi) to cover the full range of use of the dose calibrator. Oswald, et al. (*17*) suggested the use of additional attenuators to increase the range of simulation.

For the following discussion, the absolute attenuation factor is defined as the ratio of measurements without and with a shield by a perfectly linear dose calibrator. An apparent attenuation factor is one determined when the linearity of the calibrator is unknown.

The initial method (*16*) proposed was to use known or absolute attenuation factors to compute unattenuated amounts from assay results, and then find the deviations from the mean of the unattenuated values. Since then, there have been several other methods presented.

Ahluwalia (*10*) suggested using the dose calibrator in question to compute the apparent attenuation factors each time. Each set of measurements would be compared with the initial values of apparent attenuation factors. Such comparison is valid only if these reference values happen to be close to the absolute values.

Dydek, et al. (*13*) first tested the dose calibrator by the decay method to determine the nonlinearity. A new parameter called maximum allowable deviation (MAD) was defined as the difference between the maximum deviation and the action level. Apparent attenuation factors of different shields were determined. Subsequent measurements of apparent attenuation factors of the shields were compared to these values. Differences were tested against a complicated set of action levels computed from MAD. With this method of analysis, unnecessary repeats may result. One must keep track of differences in the determination of MAD and the deviations of the measured attenuation factors.

The NRC (*3*) suggested equating the initial determination of apparent attenuation factors to time of decay. Subsequent testing of nonlinearity could then be an analysis of the attenuated readings as in the decay method.

All methods except that of Davis, et al. (*16*) use the initial determinations of apparent attenuation factors as references. These values deviate from the absolute attenuation factors by the same about as the nonlinearity of the dose calibrator. Such an inaccuracy creates pitfalls in interpretation of results of subsequent testing. Furthermore, the methods of analysis appear too complex.

We recommend the method of Davis, et al. (*16*) and suggest the following protocol. First, use a sample of ^{99m}Tc with negligible ^{99}Mo contamination to determine the apparent attenuation factors of the shields (see below). Then use the decay method to test the linearity of the dose calibrator with ^{99m}Tc. As the radioactive sample decays, the series of measurements to be made should include the range of values that would result from using the shields. Choose the initial amount of ^{99m}Tc such that the contribution of ^{99}Mo remains negligible at the last measurement of the series. For example, start with 7.40 GBq (200 mCi) and cease measurement when the radioactive sample decays to 111 MBq (3 mCi). Lastly, apply the nonlinearity

correction determined in the decay method to the apparent attenuation factors to get the absolute attenuation factors.

After the calibration of the shields by the above procedure, nonlinearity testings can be performed with these shields. Attenuated readings are converted by the absolute attenuation factors to what should be the unattenuated results. Disagreement in these converted values represents nonlinearity.

Several investigators (*10,13,17*) claimed that measurements with shields could be accomplished within 3–5 min. The NRC suggested the measurements be done within 6 min (*3*). However, 6 min corresponds to 1.2% change in activity due to decay (*14*). In other words, this is error in the results if they have not been corrected for decay. This magnitude is appreciable in the determination of absolute attenuation factors and in the measurement of apparent attenuation factors when the recommended action is only 5% (*3*).

Molybdenum-99 as an impurity can affect the interpretation of results here as well. The effect is not as great as in the decay method and is illustrated by the following example. Consider an initial amount of 7.40 GBq (200 mCi) ^{99m}Tc with 1.1 MBq (30 μCi) ^{99}Mo as an impurity. The impurity has a nonmeasureable contribution to measurement without any attenuating shield. As we enclose the source by a shield and increase the amount of attenuation, the contribution from ^{99m}Tc to the assay result is reduced faster than the contribution from ^{99}Mo, which has more energetic radiation. After the attenuation of ^{99m}Tc radiation by a factor of 261 (the thickest sleeve in one of the commercial models), there would appear to be nearly 28.3 MBq (766 μCi) of ^{99m}Tc. The 1.1 MBq (30 μCi) ^{99}Mo after attenuation will emulate about 259 kBq (7 μCi) of ^{99m}Tc. That is, there is about 1% of inaccuracy due to ^{99}Mo as an impurity.

When large activity and small activity samples are used in the shield method to cover the range of activity used in a clinic, Dydek, et al. (*13*) found no significant difference in attenuation factors determined by the large activity source and the small activity source. However, Merritt (*18*) found the necessity of calibrating the shields separately for the usage of the two different activity levels. This conflict perhaps can be resolved by meticulous attention to radioactive decay and to the contribution by the ^{99}Mo impurity.

CONCLUSION

In our experience dose calibrators are highly reliable. When results of quality control procedures exceed the 5% action levels, the uncertainty in the known value of reference sources and inattention to the details of the measurements can be the culprits. If the testing protocol has been designed to avoid the pitfalls, as described in this article, repeat testing and unnecessary repair can be avoided.

When testing a dose calibrator, it is advisable to adopt an action level as low as possible. Otherwise, a dose calibrator that meets regulatory requirements can still contribute to problems. For example, the quality management program enforced by the NRC (*2*) requires the administration of certain radiopharmaceuticals to be within 10% of the prescribed dose. An apparent violation is possible if the measurements by the dose calibrator in the nuclear pharmacy and the dose calibrator in the clinic err in opposite directions, even though both dose calibrators are accurate to within 10%.

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