An Instrumented Shield System for Calibration of Technetium-99m

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Objective: The elution of ^{99m}Tc from commercial ^{99}Mo-^{99m}Tc generators and the subsequent calibration of both the bulk activity and ^{99}Mo impurity can lead to significant extremity dose to the fingers, hands and forearms. The dose arises primarily from the need to handle intense, unshielded sources when calibrations are performed with re-entry type ion chambers. The objective of this study was to develop a dose calibration system that incorporated a fully-instrumented shield for assay of gamma-emitting radioisotopes without the need for handling unshielded sources.

Methods: Prototype instrumented shield systems were tested in routine calibration of ^{99m}Tc eluted from commercial ^{99}Mo-^{99m}Tc generators to determine the quality and reproducibility of measurements. Pilot experiments were conducted to compare the extremity dose burdens from calibrations with the instrumented shield system and with standard re-entry type ionization chambers.

Results: Decay measurements with ^{99m}Tc show that the instrumented shield system provides calibrations with less than 2% systematic nonlinearity for sources of 5×10^2–1.5×10^5 MBq (15–4000 mCi). Systematic errors from source geometry variation, including changes in eluate volumes from 5–21 ml, are less than 1%. Typical calibration procedures with a re-entry type ion chamber produce dose burdens to the fingers of $(2.7$–$10.8) \times 10^{-4}$ mSv GBq^{-1} (1–4 mRem Ci^{-1}) of ^{99m}Tc handled.

Conclusion: When calibrations were performed with the instrumented shield system, the dose received could not be distinguished within the sensitivity limit of TLD finger rings used in the measurements.

Key Words: dose calibration system; extremity exposure; radioisotope generator elution

The preparation of radiopharmaceuticals for diagnostic imaging is a major source of radiation exposure in a radiopharmacy, and the dose burden from procedures of this type ha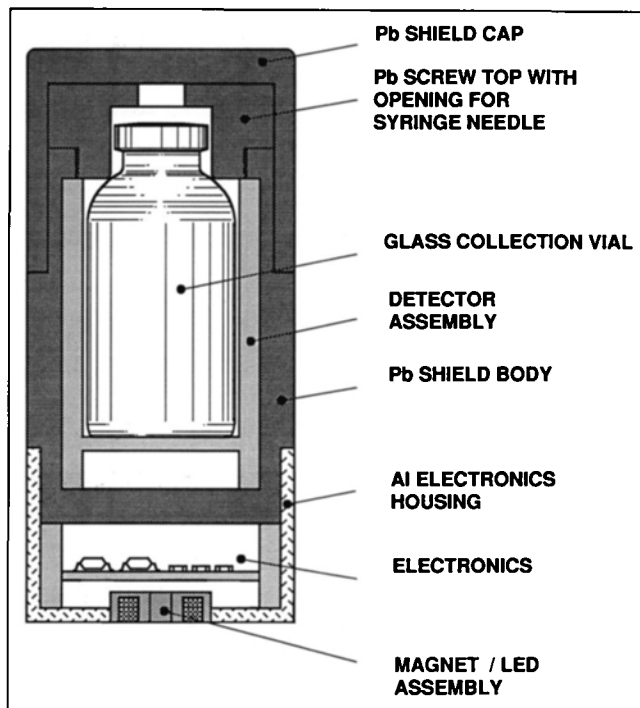s the potential to grow significantly as applications broaden and as new diagnostic agents reach the market. With the widespread use of new ^{99m}Tc-based imaging agents for myocardial perfusion studies, requiring a single patient dose of 222–740 MBq (6–20 mCi) at rest and 740–1110 MBq (20–30 mCi) under stress (*1–4*), the total dose burden in hospitals has been observed to increase significantly (*4*). Although no studies have been reported in the literature, dose burdens in a central radiopharmacy may be increasing to an even greater extent. In addition to the dose acquired during reconstitution of ^{99m}Tc-based kits and the preparation of individual doses, there is a significant potential for high exposure from handling bulk ^{99m}Tc radioactivity prior to preparation of a radiopharmaceutical. This is especially true with the curie-level sources eluted from ^{99}Mo-^{99m}Tc generators and the required assay to ensure that ^{99}Mo impurity levels are within federal limits (*5*). The introduction of new federal regulations on extremity doses and the formal institution of ALARA programs (*6*) have heightened awareness of the need to seek reasonable means for control of personnel radiation exposure.

Notwithstanding a well-designed protocol, the very intense radiation fields of such sources can lead to a significant dose in a very short time, and even the small variations in procedure that are inevitable in routine applications can increase the dose burden markedly. In this paper, the complete procedure involved in the assay of bulk ^{99m}Tc and its ^{99}Mo impurity is referred to as the calibration procedure.

The dose burden from calibration procedures arises primarily from handling unshielded elution vials in order to make activity measurements with the re-entry type ion chambers now in universal use. Three or four transfers of a vial are required in common procedures. Because the bulk activity can be as large as 500 times that contained in a single-patient dose when using commercial generators of up to 592 GBq (16 Ci), the potential dose received from calibrations can represent a significant fraction of the total dose burden from normal laboratory operations. Mechanical devices have been devised to eliminate or reduce the need for handling unshielded sources, but these have not met with wide acceptance (*7*).

FIGURE 1. Schematic of the prototype instrumented shield system.

Labels in figure:
- Pb SHIELD CAP
- Pb SCREW TOP WITH OPENING FOR SYRINGE NEEDLE
- GLASS COLLECTION VIAL
- DETECTOR ASSEMBLY
- Pb SHIELD BODY
- Al ELECTRONICS HOUSING
- ELECTRONICS
- MAGNET / LED ASSEMBLY

This paper describes the design and testing of an instrumented shield system that virtually eliminates the radiation exposure from calibration procedures of bulk ^{99m}Tc eluted from commercial ^{99m}Tc-^{99}Mo generators. Preliminary data on dose burdens when calibrations are performed with the instrumented shield system and with commercial ion chambers are reported and compared to doses calculated for a model protocol similar to those in use in many laboratories. The measured dose burdens were used to estimate quarterly dose burdens in model radiopharmacies to demonstrate the magnitude of dose reduction that could be afforded by use of the new calibration instrument.

MATERIALS AND METHODS

The Instrumented Shield System

A schematic showing the principal components of the prototype instrumented shield is shown in Figure 1. It is comprised of three main elements constructed from lead: the shield body; a screw top for loading and unloading elution vials and for location of a vial in fixed geometry relative to radiation sensors; and a shield cap that provides uniform radiation shielding in all directions when the device is fully assembled. During elution, the shield cap is removed and the shield is used in place of the standard vial shield supplied by the generator manufacturer. After calibration, the cap can be removed and activity withdrawn by syringe through the small hole located in the center of the screw top.

The prototype was designed to accept standard elution vials and to mate directly to the ^{99}Mo-^{99m}Tc generators produced by the same manufacturer (Technelite, DuPont Radio-

pharmaceutical Division, DuPont Merck Pharmaceutical Co., North Billerica, MA). The shield can contain up to 555 GBq (15 Ci) of ^{99m}Tc with a maximum exposure rate anywhere on the shield surface of less than 0.5 mR hr^{-1}. The detectors provide accurate calibration of ^{99}Tc activity in the range 5.55×10^2–5.55×10^5 MBq (15–15,000 mCi).

The complete system includes an instrumented shield, a base and a console. The shield is fitted with silicon semiconductor radiation sensors and communications electronics that output a shield identification signal and signals representing the level of contained radioactivity. The shield itself contains no power source. All electrical power is supplied by the base that also serves as the communications link between the shield and the console. The console contains the power source for the entire system and acts as the control and computation center. It contains a microprocessor for sensing and interpreting signals from a shield, for maintenance and manipulation of calibration information, and for providing output to the console's display, external computers or printers.

The base was designed to permit flexibility in placement of the system anywhere in the laboratory. Because of its small size (4.25 in (10.8 cm) diameter), it requires minimal space in a radiochemical fume hood and the console can be located where convenient. Communication between the shield and the base occurs via two mechanisms: through magnetic induction and through an optical link composed of an LED contained in the shield and a photodiode located at the center of the well in the base.

In normal operation, a shield containing eluted ^{99m}Tc is placed into a well in the base. The presence of the shield is sensed by the current drawn through the magnetic induction coupling and this signals the system to begin a measurement sequence. A signal from the console causes the shield electronics to output a signal (shield identification) that identifies the specific shield being queried and a signal representing the activity level sensed by the detectors. When received by the console, the shield identification is used to select shield-specific calibration parameters resident in the system's library. Once activity calculations are completed, the console displays the identification number of the shield, the contained activity and the time of measurement. The same information is provided to a standard RS-232 output port for use with external computers or printers. The operation is entirely automatic. Apart from placing a shield into the well in the base, the user need not intervene further to complete the desired calibration. The total time for a complete calibration procedure is less than 20 sec.

As presently configured, calibration of ^{99}Mo impurity is accomplished simply by transfer of the entire instrumented shield into a standard re-entry type ion chamber and measurement of the activity with the protocol normally followed when using a molybdenum breakthrough shield. A separate calibration factor provided with the system is then applied to the activity reported by the ion chamber to account for the shielding characteristics of the instrumented shield.
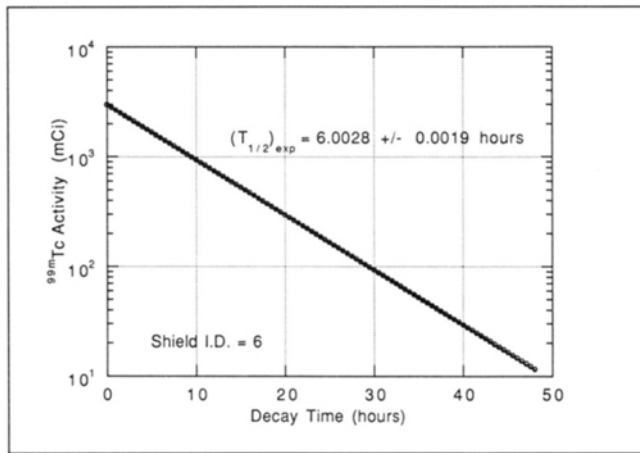
FIGURE 2. Half-life measurement of ^{99m}Tc with instrumented shield 6. The accepted half-life is 6.006 ± 0.002 hr (8).

TABLE 1
Half-Lives of ^{99m}Tc Measured with Different Instrumented Shields

Shield Identification	Initial activity (Ci)	$T_{1/2}$ (hr)	$\sigma(T_{1/2})$ (hr)
2	3.85	6.0077	0.0030
3	2.91	6.0049	0.0020
4	3.41	6.0120	0.0039
5	3.61	6.0045	0.0031
6	3.04	6.0028	0.0019
4N	3.82	6.0081	0.0018
7	3.30	6.0073	0.0021
7N	2.61	6.0074	0.0021
Mean value		6.0068 ± 0.0028	
Literature (8)		6.006 ± 0.002	

The complete calibration procedure is accomplished without removal of high-level activity from very efficient shielding. This means that the very intense radiation fields normally encountered when transferring an elution vial into and out of the ion chamber are essentially eliminated.

The prototype systems have undergone extensive testing under laboratory and field conditions to define the quality and reproducibility of activity measurements. In the following, typical data sets are presented along with summaries of field testing results.

Linearity

The linearity of response of the instrumented shield was determined by measurement of the decay of ^{99m}Tc. Typically, 103.6–140.6 GBq (2.8–3.8 Ci) of activity were eluted from a commercial generator and calibrated with an ion chamber which was itself calibrated with an NIST traceable source. The elution vial was placed into the instrumented shield and the shield's output was then monitored automatically at 30 min intervals for periods of 36–48 hr (6–8 half lives of ^{99m}Tc). A complete data set obtained in this way is shown in Figure 2 along with a least squares fit to the data. The half-life found, 6.0028 ± 0.0019 hr, is in excellent agreement with the accepted literature value (8) of 6.006 ± 0.002 hr. Similar measurements were made with 8 different shields and the data obtained are summarized in Table 1. All half-lives extracted with least squares fits are in excellent agreement with the accepted literature value. The mean half-life obtained from all fits is 6.0068 ± 0.0028 hr.

The half-life measurements provide good integral tests of the overall response of a system throughout its operating range. A more sensitive test of possible nonlinearities is obtained by comparison of individual experimental data points with activities predicted by the least squares fits at each measurement time. The quantities:

$$\delta = (A(t)_{meas}) - A(t)_{fit})/A(t)_{fit},$$

where $A(t)_{meas}$ is the measured activity at time t and $A(t)_{fit}$ is the activity calculated from the least squares fit to the data,

were used to search for nonlinearities. In the absence of systematic errors, a plot of δ versus time, or δ versus activity, should fluctuate about zero due to statistical errors only. The δ values calculated from the data shown in Figure 2 are shown in Figure 3. For activities greater than about 2.22 GBq (60 mCi), there is no discernible systematic nonlinearity within statistical errors. At lower activities a systematic pattern of nonlinearity is observed where $A(t)_{fit}$ consistently underestimates $A(t)_{meas}$. However, for activities of 925 MBq (25 mCi), the underestimate is about 0.5% and at the lower design limit of 555 MBq (15 mCi) the underestimate is less than 1.5%.

While differing in detail, plots of δ for all data sets taken with the 8 instrumented shields studied were quite similar. No systematic deviations were observed for activities greater than about 1.85–2.22 GBq (50–60 mCi) and the maximum value of δ found in this range was about ±0.005. At the measurement limit of 0.555 GBq (15 mCi), the systematic error was generally in the range 1–1.5%.
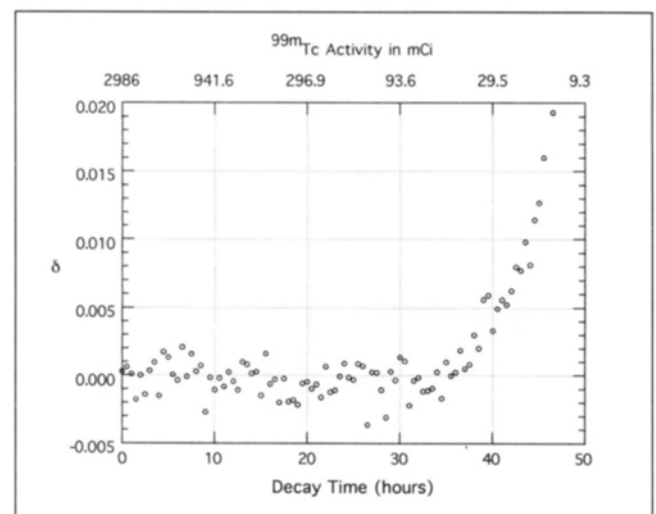
FIGURE 3. Deviations between least squares fit and experimental data. In the absence of systematic errors, the quantities δ should fluctuate statistically about zero.
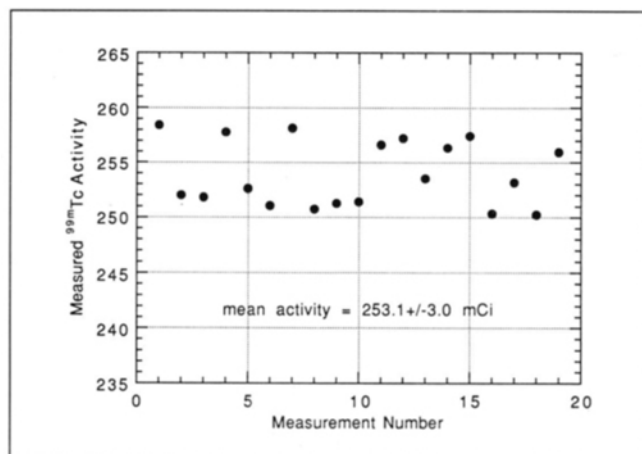
FIGURE 4. Test of effects of geometry-dependent factors on the reproducibility of ^{99m}Tc measurements with the instrumented shield system. The data points have been corrected for radioactive decay.

FIGURE 5. Frequency distribution of the ratio of ^{99m}Tc activity measured with the instrumented shield to the activity measured with an ion chamber. The data represent a composite of measurements from six different laboratories. The curve shown is a normal distribution fitted to the data with a mean of 1.024 and standard deviation of 0.019.

The activity range over which accurate measurements were permitted with these prototypes was limited by design goals and not by fundamental considerations. Indeed, preliminary tests of modified devices have demonstrated systematic nonlinearities of less than 5% down to activities as low as 37 MBq (1 mCi).

Reproducibility of Measurements

One of the principal requirements for a calibration device in the radiopharmacy is that the magnitude of the reported activity must be relatively immune to variations in counting geometry, in the dimensions of the elution vial walls and in the volume of eluate.

To test the effects of variation in vial geometry in a simple way, a nominal 9.25-GBq (250-mCi) source of ^{99m}Tc contained in a standard elution vial was placed in the instrumented shield and the activity assayed. The vial was removed from the shield to a remote location, rotated randomly, replaced in the shield and a second activity measurement was made. This procedure was repeated a total of 19 times and the resultant data are shown in Figure 4. After correcting for radioactive decay, the mean and standard deviation of the set of measurements were calculated to be 9.368 ± 0.111 GBq (253.2 ± 3.0 mCi) (±1.2%). We estimate the statistical error (percent) associated with a single measurement to be ±1% and thus the uncertainty due to geometry-dependent variations is estimated to be less than ±0.7%.

To test the sensitivity to changes in eluate volume, elutions were performed using 5.8 ml and 21 ml, the standard volumes normally used with these generators. The ratio of the activities reported by the instrumented shield system was then compared to the activity ratio reported by the ion chamber. Again assuming a ±1% statistical error in a measurement with the instrumented shield and assuming no statistical error in measurement with the ion chamber, the maximum systematic error due to volume variation in this range is conservatively estimated to be ≤0.4%.
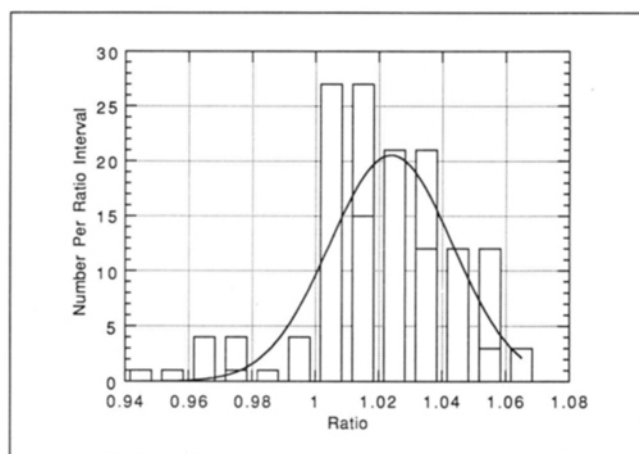
A somewhat less direct but perhaps more meaningful test of overall reproducibility under real laboratory conditions was provided by field testing of 4 different systems in 10 different laboratories. In these tests, the ^{99m}Tc contained in a vial was measured in the instrumented shield and then in a commercial ion chamber according to the standard protocol used in that laboratory. Each specimen was contained in a different elution vial and thus a reasonable sampling of the variation in vial characteristics and vial geometry within a shield was obtained. No control on the eluate volume was imposed. Composite data from 6 different laboratories are plotted as the frequency distribution of ratios of activity measured with the instrumented shield system to activity measured with an ion chamber in Figure 5. The mean and standard deviation of the normal distribution fit to the set of 102 measurements are 1.024 and 0.019, respectively.

It is not possible to extract from these data that part of the fluctuations due solely to variations in vial characteristics, vial geometry and eluate volume. The data are also affected by bias from variation in the absolute calibration of the different ion chambers used and by the fact that no corrections have been applied to account for radioactive decay between the time of measurement in the instrumented shield and the ion chamber. Typically, the sources used to check ion chamber calibrations have absolute accuracies of better than ±5% (9). The time interval between successive ^{99m}Tc assays in the two measuring devices was not reported in the field testing. However, an interval of 5 min is likely and without decay correction would lead to a ratio of 1.01 for the activity measured with the instrumented shield relative to that measured with the ion chamber. Clearly, any systematic errors due to geometry-related issues are as small or smaller than normal variations expected from statistics and calibration errors. This conclusion is consistent with the results from the controlled experiments discussed above.

TABLE 2
Raw Dosimetry Data from Calibration Procedures with Ion Chambers

Test number	Total ^{99m}Tc activity (Ci)	Normal*		Control		Average mRem Ci^{-1}	
		Left	Right	Left	Right	Normal	Control
1	27	30	30	—	—	1.11	—
2	101	120	130	120	120	1.23	1.19
3	17	120	30	—	—	4.41	—

*Normal refers to the TLD finger rings worn during actual calibrations. In all cases, the dose determined on finger rings used with the instrumented shield calibrations was not discernible.

Extremity Dose Burdens From a Calibration Procedure

The dose burden from a single calibration of ^{99m}Tc and its ^{99}Mo impurity is very sensitive to many factors including the detailed protocol specified in a laboratory, the experience of the user and her implementation of the protocol, and the activity level at the time of assay. Notwithstanding a well-thought-out protocol and a highly skilled practitioner, the actual dose received from an assay sequence is likely to vary because of the inevitable variations in implementation that occur under real laboratory conditions. As discussed further below, in the section Model Estimates of Dose Burdens, even a small departure from good laboratory practice can result in a large change in extremity dose.

While it will take a much larger and more detailed study regimen to obtain a statistically valid representation of the dose burdens, we have performed three sets of measurements to obtain estimates of the burden from a single calibration procedure and the extent of dose reduction possible through use of the instrumented shield system.

In the first test, designed to minimize differences between repetitions of a procedure, a fixed quantity of ^{99m}Tc contained in a standard elution vial was subjected to repeated measurement of ^{99m}Tc and ^{99}Mo impurity by use of the instrumented shield system. Following this, the assays were performed sequentially with use of a commercial ion chamber of the re-entry type using the standard procedure in the laboratory. During each set of measurements different TLD finger rings were worn by the user. All measurements were completed in a single day and the finger rings were processed simultaneously by a commercial laboratory to determine the effective total dose equivalent to the finger on which the ring was worn. To ensure that a reasonably large response was likely, the ^{99m}Tc activity used in each assay was about 92.5 MBq (2.5 Ci) and the total ^{99m}Tc activity handled was greater than 0.925 GBq (25 Ci).

In the second test, designed to assess dose burdens under more realistic laboratory conditions, a group of 5 technicians in an industrial quality control laboratory were requested to calibrate ^{99m}Tc during their normal laboratory duties that included a number of different procedures with several different isotopes. When calibrating the ^{99m}Tc, the user per-

formed a calibration procedure with the instrumented shield system and immediately thereafter with an ion chamber. Three sets of TLD finger rings were used. One set of rings was worn by all 5 users when calibrating with the instrumented shield system, a second set when calibrating with the ion chamber and the third set was worn when calibrating with either instrument and served as a control. At all other times, the finger rings were stored in a lead shield to prevent exposure from other laboratory operations. The measurements took place over a period of 2 wk to obtain reasonable exposure levels and the finger rings were processed simultaneously.

In the third test, designed to assess dose burdens in a nuclear pharmacy environment, calibrations were performed by an experienced board-certified nuclear pharmacist in a hospital radiopharmacy during the normal course of his laboratory functions. The protocol was similar to that described for the second test but no controls were included. Again the measurements extended over a period of 2 wk.

The total dose recorded by each finger ring was normalized by the total ^{99m}Tc activity handled in the calibrations and the result reported as mRem Ci^{-1} of ^{99m}Tc handled. These quantities then represent the dose equivalent to soft tissue in the vicinity of the finger ring per 37 GBq (1.0 Ci) of ^{99m}Tc, averaged over all of the calibrations performed in a single test sequence.

The data obtained from these studies are listed in Table 2. In each test, the rings worn when the instrumented shield was used for the calibrations indicated no absorbed dose within the sensitivity of the measurements ($\leq$10 mRad). In each case, however, absorbed dose was registered when the ion chamber was used. It is interesting to note that the average dose burden was quite similar for the two laboratories in the same organization (Tests 1 and 2) where the protocols are similar and where the technical staff has undergone the same training program. In the one case where a reasonable control was included (Test 2), there is no evidence for bias or significant scatter in the TLD readings. Contrary to the others, the data from Test 3 indicate a large difference in exposure between the left and right hands and suggests that the calibration protocol in this laboratory was significantly different from the other two.

We stress that these data must be considered preliminary and cannot be used to specify the dose burden from a calibration procedure in any given laboratory for the reasons discussed above. Nevertheless, they are at least indicative that a dose per unit activity handled of $(2.7–10.8) \times 10^{-4}$ mSv GBq^{-1} (1–4 mRem Ci^{-1}) for a single calibration procedure with a re-entry type ion chamber can be found with common protocols. Given the variation in protocols in actual use and the high sensitivity to small changes in technique, the range indicated by the tests is not unexpected. Further, the data obtained from these tests are consistent with the dose estimates calculated below for a model protocol similar to one used in many laboratories.

Model Estimates of Dose Burdens

In the absence of detailed empirical information, we performed a few simple calculations to try to understand the magnitudes of the dose burdens reported above and to estimate what significance they have with respect to the total dose burden in a radiopharmacy. For this purpose we considered the details of one common calibration procedure which is briefly described as follows. A generator elution is performed using a standard elution vial contained in a standard vial shield. After elution, the vial shield is opened, the vial dropped directly into a vial holder in the ion chamber and the ^{99m}Tc activity is calibrated. Following calibration, the vial is removed from the ion chamber with the aid of 12-inch (30.5-cm) forceps and placed into the vial shield. A molybdenum breakthrough shield is placed into the ion chamber for background determination and then removed. The vial is dropped directly from the vial shield into the breakthrough shield, the breakthrough shield is assembled and then placed into the ion chamber for determination of ^{99}Mo impurity. Finally the elution vial is dropped back into the standard vial shield. As in normal procedures, there is no direct handling of an active elution vial.

In this procedure the most dose-sensitive step, which is the step most readily subjected to reliable analysis, is the transfer of the unshielded vial from the ion chamber back into the vial shield with the aid of forceps. With good technique this step can be accomplished in 2–4 sec. When 12-inch forceps are used, the distance between the fingers and the center of the vial is likely to be 8–9 in (20.3–22.9 cm). The dose equivalent rate to soft tissue at 8.5 in (21.6 cm) from a 37 GBq (1 Ci) unshielded point source of ^{99m}Tc is estimated to be 3.1×10^{-3} mSv s^{-1} (0.31 mRem s^{-1}) from the 140.5 keV γ-rays[1]. Thus, the dose received in the most dose-sensitive step of the calibration procedure is expected to be in the range $(1.7–3.4) \times 10^{-4}$ mSv GBq^{-1} (0.63–1.26 mRem Ci^{-1}) of ^{99m}Tc to the fingers of the hand involved in the transfer. With slower response during the transfer or a smaller distance between the hand and the elution vial during transfer, larger dose burdens will result and vice versa.

It is very difficult to estimate the dose burden from the remaining steps in the procedure. With good technique, the fingers will be almost completely shielded from the direct radiation field but some exposure of other parts of the hand and forearm is inevitable. Unfortunately, small lapses in technique can produce significant contributions to the dose from the whole procedure. For example, when reassembling the standard vial shield or breakthrough shield after a transfer, parts of the hand can be within 2–4 in (5.08–10.16 cm) of the eluate center. The dose equivalent rate at a 3-in (7.62 cm) distance from a 37 GBq (1 Ci) ^{99m}Tc source is about 6.76×10^{-4} mSv s^{-1} MBq^{-1} (2.5 mRem s^{-1} Ci^{-1}). Clearly, only a fraction of a second exposure can result in doubling the total dose estimated for the procedure. These calculations lend credence to the experimental findings that single-procedure dose burdens per unit activity handled lie in the range of $(2.7–10.8) \times 10^{-4}$ mSv GBq^{-1} (1–4 mRem Ci^{-1}) of ^{99m}Tc handled when calibrating with an ion chamber.

We can now use the experimental data to make estimates of the quarterly dose from the calibration procedure in model radiopharmacies. As a first example, we consider a relatively small but efficient radiopharmacy that purchases one 92.5 GBq (2.5 Ci) ^{99}Mo-^{99m}Tc generator per week, elutes each generator once a day from the calibration date to expiration date (13 days), and uses all available ^{99m}Tc. This implies that the average activity eluted per day per generator is about 30.4 GBq (822 mCi). Since the average number of generators eluted per day would be 2, the total average activity eluted per day is about 60.8 GBq (1.64 Ci) and quarterly elutions would amount to about 5.53×10^3 GBq (150 Ci). With a dose equivalent to the fingers of $(2.7–10.8) \times 10^{-4}$ mSv GBq^{-1} (1–4 mRem Ci^{-1}) of activity handled, the quarterly dose burden from the calibration procedure alone would be about 1.5–6.0 mSv (150–598 mRem).

Because the dose burden varies linearly with activity utilization at the time of elution, these estimates are easily applied to estimate dose burdens for other laboratory conditions. For example, a large central laboratory might purchase one 92.5 GBq (2.5 Ci) generator per day. Under similar conditions of activity utilization, the total dose burden will simply be larger by a factor of 7.

DISCUSSION AND CONCLUSION

We have described a prototype instrumented shield system that can effectively eliminate the dose burden associated with the assay of bulk ^{99m}Tc and its ^{99}Mo impurity. Field tests demonstrate that the device can accomplish the required calibrations under routine laboratory conditions with high reliability and with some increase in efficiency relative to procedures that use ion chambers of the re-entry type because of reduction in the number of operations required to complete a calibration procedure.

The total dose to nuclear medicine personnel from calibration of bulk ^{99m}Tc and its ^{99}Mo impurity can be quite substantial. The fraction of total dose from this activity will vary

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[1] The calculations here neglect the dose from x-rays and conversion electrons emitted in the decay of ^{99m}Tc. These radiations are absorbed to a large extent by the saline eluate and the glass walls of the elution vial.

from laboratory to laboratory and from individual to individual. Simple estimates suggest it can represent perhaps 25–40% of the total dose burden in many laboratories. This dose is effectively eliminated with use of the new instrumented shield and thus a very significant reduction in total extremity dose is possible with its use.

The technology contained in the instrumented shield system is not restricted to use with ^{99m}Tc but can be extended to calibrate any of the γ-emitting isotopes commonly used in nuclear medicine, including those used with PET imaging. Direct measurement of the molybdenum impurity in eluted ^{99m}Tc can be included within the system. The technology can be applied to a system that contains and calibrates kit vials as well as to a system that permits the preparation of single-dose quantities of radiopharmaceuticals in a syringe. Taken together, these extensions hold the promise of a very marked improvement in radiation safety in the radiopharmacy. High-dose burdens are no longer a necessary consequence of the preparation and handling of modern radiopharmaceuticals.

ACKNOWLEDGMENTS

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