GENERATOR-PRODUCED $^{99m}TcO_4^-$: CARRIER FREE?

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A solution of $^{99m}TcO_4^-$, as eluted from a ^{99}Mo-^{99m}Tc radionuclide generator contains a greater chemical quantity of technetium than that attributable to the metastable isomer alone. The isomeric transition of the radionuclide of interest, ^{99m}Tc, gives rise to a determinable and chemically significant quantity of technetium carrier, ^{99}Tc. A method is presented for calculating the total chemical quantity of technetium in a generator eluate.

In nuclear chemistry the term carrier-free is rather loosely defined. The dichotomy of the definition may be due to extrapolation of the word "carrier" to the definition of "carrier-free." Carrier is a nonradioactive elemental or molecular species that is added to its radioactive analog for the purpose of separation, etc. From this it follows that a carrier-free preparation would be a preparation to which no stable species had been added.

Another definition widely accepted is: "an adjective applied to one or more radioactive isotopes of an element in minute quantity, essentially undiluted with stable isotope carrier" (*1*). This is interpreted to exclude the presence of any stable analog whether or not it had been purposely added. Either of these definitions would indicate that the ^{99}Mo-^{99m}Tc generator eluate is carrier-free, in the first case due to a lack of added material, and in the second case because the decay product, ^{99}Tc, is unstable.

In point of fact, however, when considering molar reactivity or absolute amount of chemical species present, a radionuclide that decays by isomeric transition, e.g. ^{99m}Tc, is never entirely free of carrier, which in this case is the relatively stable ground state species ^{99}Tc. The physical quantity of TcO_4^- in an eluate cannot be determined from the activity of the metastable isomer alone.

While for most applications the amount of ^{99}Tc in a preparation is minute and insignificant neither of the above definitions are useful, for example, when considering molar ratios of reducing agents in a radiopharmaceutical preparation. Since ^{99m}Tc is such an important radionuclide in nuclear medicine and because quantitative technetium chemistry requires a consideration of molar concentration, the amount of ^{99}Tc must be known.

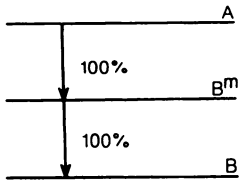

FIG. 1. Generator decay scheme involving metastable daughter.

The purpose of this communication is to elucidate the mathematical relationship of physical quantities of ^{99}Mo decay products as a function of time and to propose a simple method for calculating the total quantity of technetium (both 99m and 99) in a generator eluate. We also hope to clarify the meaning of the term carrier-free, which we feel should be reserved for those materials having maximum attainable specific activity.

GENERAL APPLICATION

In the general case where a radionuclide generator has a decay scheme as shown in Fig. 1, the amount of nuclide B in the generator is a function of time since prior elution. If it is assumed that (A) at the time of initial elution, $t = 0$, only radionuclide A is present on the column, and (B) that B is stable or has a decay constant small enough to be reasonably disregarded, then the following equations represent

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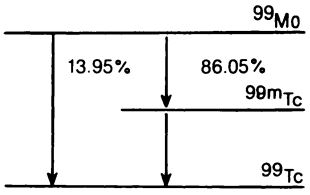

FIG. 2. Simplified decay scheme for ^{99}Mo-^{99m}Tc generator.

the number of atoms of decay products present on the column at any time, t (*2*):

$$N_{(B^m)} = \frac{\lambda_1}{\lambda_2 - \lambda_1} N_A^0 (e^{-\lambda_1 t} - e^{-\lambda_2 t}) \quad (1)$$

$$N_{(B)} = N_A^0 (1 + \frac{\lambda_1}{\lambda_2 - \lambda_1} e^{-\lambda_2 t} - \frac{\lambda_2}{\lambda_2 - \lambda_1} e^{-\lambda_1 t}) \quad (2)$$

Thus the mole-fraction of B present at any time on the column as the metastable B^m is given by:

$$\frac{N_{(B^m)}}{N_{(total)}} = \frac{N_{(B^m)}}{N_{(B)} + N_{(B^m)}} \quad (3)$$

When Eqs. 1 and 2 are substituted into Eq. 3 and reduced to its simplest form, the mole-fraction of B present in the metastable form B^m as a function of time is obtained. This relation is:

$$\frac{N_{(B^m)}}{N_{(total)}} = \frac{\lambda_1 (e^{-\lambda_1 t} - e^{-\lambda_2 t})}{(\lambda_2 - \lambda_1)(1 - e^{-\lambda_1 t})} \quad (4)$$

Equation 4 therefore represents the fraction of B present as B^m at any time following prior elution. This equation may be used for any generator system represented by the decay scheme shown in Fig. 1, and where the two assumptions above are satisfied, e.g. the Sn^{113}-In^{113m} generator.

^{99}Mo-^{99m}Tc GENERATOR

As applied to the ^{99}Mo-^{99m}Tc generator, the calculation is somewhat more complicated due to the branching decay of ^{99}Mo (Fig. 2). In this case, since 86.05% of ^{99}Mo decays to ^{99m}Tc (*3*), $N_{(99m)} = 0.8605\ N_{(B^m)}$. The amount of ^{99}Tc present is equal to the sum of ^{99}Tc generated through each of the two routes of decay. The ^{99}Tc generated by decay of ^{99m}Tc is equal to $0.8605\ N_{(B)}$ while the amount of ^{99}Tc produced directly from ^{99}Mo accumulates according to the general exponential recovery equation (*4*):

$$N'_{(B)} = N_A^0 (1 - e^{-\lambda_1 t}) \quad (5)$$

Since 13.95% of ^{99}Mo decays by the latter route, the total amount of ^{99}Tc is expressed by the relation:

$$N_{(99)} = 0.1395\ N'_{(B)} + 0.8605\ N_{(B)} \quad (6)$$

Since

$$\frac{N_{(99m)}}{N_{(total)}} = \frac{N_{(99m)}}{N_{(99)} + N_{(99m)}},$$

$$\frac{N_{(99m)}}{N_{(total)}} = \frac{0.8605\ N_{(B^m)}}{0.1395\ N'_{(B)} + 0.8605\ N_{(B)} + 0.8605\ N_{(B^m)}}$$

Further simplification yields,

$$\frac{N_{(99m)}}{N_{(total)}} = \frac{N_{(B^m)}}{0.1621\ N'_{(B)} + N_{(B)} + N_{(B^m)}} \quad (7)$$

When Eqs. 1, 2, and 5 are substituted into Eq. 7, and reduced to its simplest form, the relation is:

$$\frac{N_{(99m)}}{N_{(total)}} = \frac{\lambda_1 (e^{-\lambda_1 t} - e^{-\lambda_2 t})}{1.1621\ (\lambda_2 - \lambda_1)(1 - e^{-\lambda_1 t})} \quad (8)$$

where (*5*)

TABLE 1. 99m MOLE-FRACTIONS FOR ^{99}Mo-^{99m}Tc GENERATOR*

Days since prior elution	Hours since prior elution							
	0	3	6	9	12	15	18	21
0	—	0.7270	0.6191	0.5315	0.4599	0.4009	0.3520	0.3112
1	0.2769	0.2479	0.2232	0.2020	0.1838	0.1679	0.1540	0.1418
2	0.1311	0.1215	0.1129	0.1053	0.0984	0.0921	0.0865	0.0813
3	0.0766	0.0722	0.0682	0.0646	0.0612	0.0580	0.0551	0.0523
4	0.0498	0.0474	0.0452	0.0431	0.0411	0.0393	0.0375	0.0359
5	0.0344	0.0329	0.0315	0.0302	0.0290	0.0278	0.0266	0.0256
6	0.0246	0.0236	0.0227	0.0218	0.0210	0.0202	0.0194	0.0187
7	0.0180	0.0173	0.0167	0.0161	0.0155	0.0149	0.0144	0.0139
8	0.0134	0.0129	0.0125	0.0120	0.0116	0.0112	0.0108	0.0104
9	0.0101	0.0097	0.0094	0.0091	0.0088	0.0085	0.0082	0.0079
10	0.0076	0.0074	0.0071	0.0069	0.0067	0.0065	0.0062	0.0060
11	0.0058	0.0056	0.0055	0.0053	0.0051	0.0049	0.0048	0.0046
12	0.0045	0.0043	0.0042	0.0041	0.0039	0.0038	0.0037	0.0036
13	0.0034	0.0033	0.0032	0.0031	0.0030	0.0029	0.0028	0.0027

* Fraction of technetium in metastable form.

$$\lambda_1 = \frac{\ln 2}{66.48\ \text{hr}} = 0.010426\ \text{hr}^{-1}$$

$$\lambda_2 = \frac{\ln 2}{6.02\ \text{hr}} = 0.11514\ \text{hr}^{-1}$$

While Eq. 8 is a straightforward relationship, the calculation is cumbersome and it is useful to refer to a table of 99m mole-fractions, i.e., precalculated values of this function at various times (Table 1).

CONCLUSION

Thus with a simple calculation it is possible to determine the total quantity of technetium present based on time since previous elution. Since

$$A_{(99m)} = \lambda_2 N_{(99m)}$$

$$\text{and } N_{(total)} = \frac{N_{(99m)}}{(99\text{m mole-fraction})}$$

then

$$N_{(total)} = \frac{A_{(99m)}}{(\lambda_2)\ (99\text{m mole-fraction})} \qquad (9)$$

Equation 9 then permits a simple calculation of the total physical quantity of technetium based on the activity of ^{99m}Tc at the time of elution and on the time elapsed since prior elution. It is apparent that the chemical quantity of technetium in a preparation is always greater than that of the metastable isomer alone and that by the definition of carrier-free as suggested above, i.e., maximum attainable specific activity, ^{99m}Tc is never carrier-free.

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