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ERRORS IN THE DOSIMETRY OF ^{198}Au THERAPY

by

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Radioactive gold has now completely replaced radon, and long-lived cobalt-60 or radium in mould and implant therapy because of the following advantages: (1) avoidance of hospitalization or frequent visits of the patient, (2) protection of adjacent radiosensitive tissues, (3) no recovery of the radioactive substances from moulds or implants is needed, and (4) little radiation hazards to radiation and non-radiation workers.

The frequent use of ^{198}Au warrants careful estimation of the dose. The current practice with regard to ^{198}Au therapy is either to apply the rules and tables of PATERSON & PARKER (1938) to find the number of mg · h of radium required to deliver a certain dose to a specific area of tissue, to convert the mg · h into mCi of radon and then to the equivalent mCi of ^{198}Au or from the relation that 1 mCi of ^{198}Au after complete decay is equivalent to 28.30 mg · h of radium. Two errors are inherent in this procedure of dose estimation.

The first error lies in the value of the specific gamma ray constant, Γ, for ^{198}Au used in the calculation of the equivalence of radon to ^{198}Au. In standard textbooks the equivalence is given as:

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Table 1

The different values for the specific gamma ray constant, Γ, for ^{198}Au as given in the literature

$\Gamma \frac{(R \cdot cm^2)}{mCi \cdot h}$	Reference
2.19	Greenfield (1965)
2.27	Wagner (1968)
2.3	Silver (1968)
2.308	Henry (1969)
2.34	Johns (1969)
2.35	Hine (1956)
2.40	Henschke (1958)
2.42	Sinclair (1952)
2.43	A.E.C.L.
2.49	Present work

1 mCi of radon = 5.00 mCi of ^{198}Au = 26.6 mg·h radium equivalent (Johns 1969).

One should remember that this equivalence is valid only when both radon and ^{198}Au decay completely. In other words, the dose delivered at 1 cm by 1 mCi of radon, when it is left to decay completely is equal to the dose delivered at 1 cm by 5.0 mCi of ^{198}Au when the latter is also left for total decay.

Different authors give different values for the equivalence. This difference arises as already mentioned by using different values of Γ for ^{198}Au; these are summarized in Table 1. Hence, the literature is in complete disagreement regarding the value of Γ for ^{198}Au.

From the data given in Table 2, one usually calculates the equivalence as follows:

Total exposure dose at 1 cm from 1 mCi of a radioisotope after it decays completely equals $\Gamma \times$ average life. In the case of radon it equals 8.25×133 R, and in the case of ^{198}Au 2.34×93.6 R.

Therefore,

$$1 \text{ mCi of radon} = \frac{8.25 \times 133}{2.34 \times 93.6} = 5.00 \text{ mCi of } {}^{198}\text{Au}.$$

This equivalence is valid only when the radioisotope decays completely.

Since the different values of Γ affect the equivalence of radon to ^{198}Au, it was decided to calculate the value of Γ for ^{198}Au from first principles which are described elsewhere (Loevinger et coll. 1956, Smith 1965, Smith et coll. 1968).

Table 2

Comparison of physical parameters for ^{222}Rn and ^{198}Au

Radionuclide	Half-life	Mean-life	$\Gamma \frac{(R \cdot cm^2)}{mCi \cdot h}$
^{222}Rn	92 h	133 h	8.25
^{198}Au	65 h	93.6 h	2.34

Data from the decay scheme of ^{198}Au (see Figure) are taken to calculate the contributions of γ_1, γ_2 and γ_3 to the value of Γ (HAMILTON et coll. 1962, STROMINGER et coll. 1958).

The values for conversion coefficients α_K, α_L and α_{M+N} given by PARASIGNAULT (1966) for the 0.412 MeV gamma rays have been taken for the calculations as these values readily agree with those given in the NUCLEAR DATA SHEETS (1962), and by HAMILTON et coll. 1965—66), DILLMAN (1969) and LEDERER et coll. (1968).

For 0.412 MeV γ_1:

$\alpha_t = 0.0426$
$\alpha_K = 0.0283$
$\alpha_L = 0.0111$
$\alpha_{M+N} = 0.0031$

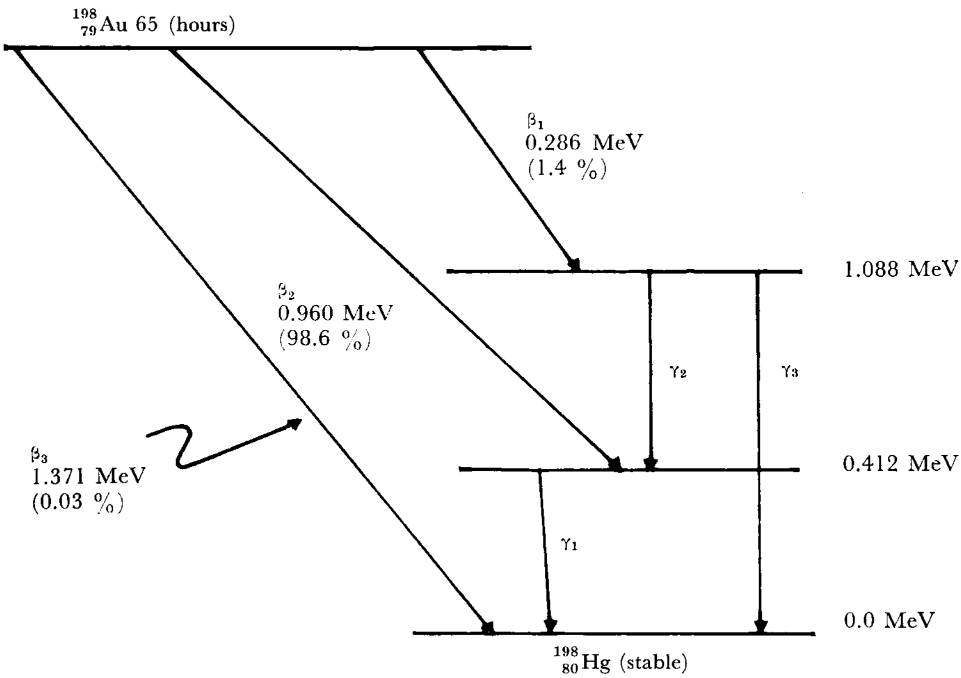
where, α_t is the total conversion coefficient.

The calculations for determining the value of Γ for ^{198}Au are summarized in Table 3. The value obtained is 2.49 R · cm^2/mCi ·h.

$$1 \text{ mCi of radon destroyed} = \frac{8.25 \times 133 \text{ R}}{2.49 \times 93.6 \text{ R}} = 4.70 \text{ mCi of } ^{198}\text{Au after}$$

complete decay.

For the Γ value of 2.49 R · cm^2/mCi ·h, 1 mCi of ^{198}Au after complete decay is equal to 28.30 mg · h of radium equivalent, where as for Γ value of 2.32 R · cm^2/mCi · h. 1 mCi of ^{198}Au after complete decay is equal to 26.30 mg · h of radium equivalent. This affects the dosimetry of both permanent and removable implants. If 1 mCi of ^{198}Au after complete decay is taken as 26.3 mg · h radium equivalent, then one is actually overestimating the dose by 8.0 %. In other words, if a dose of 6 000 rad is estimated to a permanent implant, then the correct dose delivered will be 108 % of the estimated dose or 6 480 rad. Then one can see that the lower Γ value for ^{198}Au results in overestimation of the dose by 8.0 %. This is illustrated in Table 4.



Decay scheme of ^{198}Au. γ_1 = 0.412 MeV (99.66 %), γ_2 = 0.676 MeV (1.06 %), γ_3 = 1.088 MeV (0.2 %).

The second error arises from the fact that dose estimation is affected if the treatment time is less or considerably less than the total decay time of ^{198}Au as in the case of moulds and removable implants. For practical purposes 30 days is taken as infinite time during which ^{198}Au decays completely.

The error can be illustrated by taking a hypothetical case in which an exposure of 6 000 R to a skin surface of 10 cm^2 is desired, using a mould at 0.5 cm treatment distance for 7 days. From the tables given by PATTERSON & PARKER, one finds that 1 410 mg · h is required to deliver 6 000 R. From other tables (MEREDITH 1958, WILSON 1948) one finds that 1 mCi of radon in 7 days has a cumulative dose of 95.51 mg · h.

Hence the number of

$$\text{mCi of radon} = \frac{1\,410 \text{ mg} \cdot \text{h}}{95.51 \text{ mg} \cdot \text{h/mCi}} = 14.76.$$

One may calculate the number of mCi of ^{198}Au required as equal to 14.76 × 5.00 = 73.8 mCi of ^{198}Au, whereas according to the present work 14.76 × 4.7 = 69.4 mCi of ^{198} Au are required.

Table 3

Calculation of Γ for ^{198}Au

Type of radiation	Photon energy E_i (MeV)	Fract. freq./ disint. n_i	$\mu_{en(air)i}$ cm^{-1}	$\Gamma_i \frac{R \cdot cm^2}{mCi \cdot h}$
γ_1	0.412	0.956	3.82×10^{-5}	2.26
Kα rtg ray	0.068	0.019	3.60×10^{-5}	0.007
Kβ rtg ray	0.078	0.006	3.20×10^{-5}	0.002
γ_2	0.676	0.010	3.80×10^{-5}	0.041
γ_3	1.088	0.002	3.54×10^{-5}	0.011
Brems-strahlung	0.33	0.086	3.80×10^{-5}	0.168
Total				2.49

Table 4

Variation in estimated dose using different values for Γ

$\Gamma \frac{(R \cdot cm^2)}{mCi \cdot h}$	$\frac{mCi\ ^{198}Au}{mCi\ Rn\ for\ complete\ decay}$	mg·h (radium equivalent)	Dose estimate for 6000 rad	
			If Γ = 2.5 is true value	If Γ = 2.32 is true value
2.12	5.51	24.13	7000 rad	6500 rad
2.32	5.09	26.30	6500 rad	6000 rad
2.50	4.70	28.30	6000 rad	5500 rad

Table 5

The inverse variation of the percentage error of dose estimation with overall treatment time, if correction is not made

Overall treatment time in days	Percentage error
5	28
6	21.5
7	16.5
8	13
9	10
10	8
12	4.8

This calculation is in error because the equivalence between radon and ^{198}Au does not hold good when the treatment time is short, about one week. As already pointed out, the equivalence is true only when the mould or implant is left till the complete disintegration of ^{198}Au or 30 days. In this case where the dose is to be delivered in 7 days, the equivalent value of ^{198}Au in mCi (4.70) should be multiplied by a factor of 0.86 which is the ratio of the percentage of radon decayed in 7 days to the percentage of ^{198}Au decayed in 7 days.

Hence, the correct number of mCi of ^{198}Au required will be $14.76 \times 4.7 \times 0.86 = 59.69$ mCi of ^{198}Au.

Thus, without the correction factor the calculation results in higher estimation of dose, an increase of 16.3 % or 6 978 R. This error varies inversely with treatment time as shown in Table 5.

The calculation to obtain the correct number of mCi of ^{198}Au can be cross-checked to ensure the correct answer by the following two methods.

(1) In 7 days 83.46 % of ^{198}Au decays completely. Out of the initial 59.69 mCi of ^{198}Au, after 7 days $59.69 \times 0.8346 = 49.82$ mCi of ^{198}Au should have decayed completely.

49.82 mCi of ^{198}Au is equivalent to 49.82/4.7 or 10.60 mCi of radon completely decayed. Then the cumulative dose will be equal to $10.60 \times 133 =$ 1 410 mg · h radium equivalent.

This can also be verified as follows:

59.69 mCi in 7 days is equal to $59.69 \times 0.8346 = 49.82$ mCi of ^{198}Au decayed completely, which is equal to 49.82 mCi $\times$ 28.30 mg·h/mCi = 1 410 mg · h equivalent.

(2) The number of

$$\text{mCi of } ^{198}\text{Au required} = \frac{1\,410 \text{ mg}\cdot\text{h}}{28.3 \text{ mg}\cdot\text{h/mCi}} = 49.82.$$

49.82 mCi of ^{198}Au in 7 days will deliver a cumulative dose equivalent to $49.82 \times 0.8346 \times 28.30$ mg · h radium = 1 177 mg · h = 4 998 R, which is obviously incorrect.

Hence the correct number of

$$\text{mCi of } ^{198}\text{Au required} = \frac{1\,410 \text{ mg}\cdot\text{h}}{28.30 \times 0.8346 \text{ mg}\cdot\text{h/mCi}} = 59.69 \text{ mCi}.$$

In order to simplify the calculations and avoid the error discussed in this paper, Table 6 was prepared which directly gives the percentage decay of ^{198}Au in any specific period of time and the corresponding cumulative dose in mg · h of radium equivalent, without reference to radon, which is useful in the estimation of the dose by the method of PATERSON & PARKER.

Table 6

Decay of ^{198}Au and the equivalent dose in mg · h radium equivalent

Days	Hours	Total number of hours	Percentage of ^{198}Au decayed	Equivalent mg·h per initial mCi of ^{198}Au	
				$\Gamma = 2.32$	$\Gamma = 2.49$
	0	0	00.00	0.00	00.0
	1	1	1.07	0.28	0.30
	2	2	2.12	0.55	0.59
	3	3	3.16	0.84	0.89
	4	4	4.19	1.10	1.18
	5	5	5.21	1.37	1.47
	6	6	6.22	1.63	1.76
	7	7	7.22	1.89	2.04
	8	8	8.21	2.15	2.32
	9	9	9.19	2.40	2.59
	10	10	10.16	2.66	2.87
	11	11	11.11	2.94	3.17
	12	12	12.06	3.16	3.41
	13	13	13.00	3.40	3.67
	14	14	13.92	3.64	3.93
	15	15	14.84	3.89	4.20
	16	16	15.75	4.13	4.46
	17	17	16.65	4.37	4.71
	18	18	17.53	4.60	4.96
	19	19	18.41	4.81	5.19
	20	20	19.28	5.05	5.45
	21	21	20.14	5.29	5.71
	22	22	20.99	5.50	5.94
	23	23	21.83	5.70	6.15
1	0	24	22.67	5.94	6.41
	1	25	23.49	6.15	6.64
	2	26	24.30	6.35	6.85
	3	27	25.11	6.56	7.08
	4	28	25.91	6.77	7.31
	5	29	26.70	7.00	7.56
	6	30	27.48	7.20	7.77
	7	31	28.25	7.38	7.97
	8	32	29.01	7.58	8.18
	9	33	29.77	7.78	8.40
	10	34	30.52	8.01	8.65
	11	35	31.26	8.19	8.84
	12	36	31.99	8.36	9.02
	13	37	32.72	8.54	9.22
	14	38	33.43	8.74	9.43
	15	39	34.14	8.94	9.65

Table 6 *(cont.)*

Days	Hours	Total number of hours	Percentage of ^{198}Au decayed	Equivalent mg·h per initial mCi of ^{198}Au	
				$\Gamma = 2.32$	$\Gamma = 2.49$
	16	40	34.84	9.13	9.86
	17	41	35.54	9.30	10.04
	18	42	36.22	9.48	10.23
	19	43	36.90	9.65	10.42
	20	44	37.58	9.85	10.63
	21	45	38.24	10.01	10.81
	22	46	38.90	10.18	10.99
	23	47	39.55	10.35	11.17
2	0	48	40.19	10.52	11.36
	1	49	40.83	10.69	11.54
	2	50	41.46	10.83	11.69
	3	51	42.08	11.03	11.91
	4	52	42.70	11.19	12.08
	6	54	43.92	11.53	12.45
	8	56	45.10	11.83	12.77
	10	58	46.27	12.14	13.11
	12	60	47.41	12.44	13.43
	14	62	48.52	12.71	13.72
	16	64	49.61	13.01	14.05
	18	66	50.68	13.29	14.35
	20	68	51.73	13.54	14.62
	22	70	52.75	13.80	14.90
3	0	72	53.75	14.08	15.20
	3	75	55.21	14.43	15.58
	6	78	56.63	14.85	16.03
	9	81	58.00	15.25	16.47
	12	84	59.33	15.57	16.81
	15	87	60.61	15.91	17.18
	18	90	61.86	16.23	17.52
	21	93	63.06	16.54	17.86
4	0	96	64.23	16.85	18.19
	3	99	65.36	17.17	18.54
	6	102	66.46	17.40	18.79
	9	105	67.52	17.66	19.07
	12	108	68.55	17.92	19.35
	15	111	69.54	18.18	19.63
	18	114	70.50	18.41	19.88
	21	117	71.44	18.69	20.18
5	0	120	72.34	18.94	20.45
	4	124	73.50	19.27	20.81
	8	128	74.61	19.55	21.11

Table 6 *(cont.)*

Days	Hours	Total number of hours	Percentage of ^{198}Au decayed	Equivalent mg·h per initial mCi of ^{198}Au	
				Γ = 2.32	Γ = 2.49
	12	132	75.67	19.85	21.43
	16	136	76.69	20.08	21.68
	20	140	77.67	20.31	21.93
6	0	144	78.61	20.61	22.25
	4	148	79.51	20.87	22.53
	8	152	80.36	21.12	22.80
	12	156	81.19	21.32	23.02
	16	160	81.98	21.52	23.24
	20	164	82.73	21.70	23.43
7	0	168	83.46	21.88	23.62
	8	176	84.82	22.25	24.03
	16	184	86.06	22.56	24.36
8	0	192	87.21	22.87	24.69
	8	200	88.26	23.16	25.01
	16	208	89.22	23.41	25.28
9	0	216	90.11	23.62	25.50
10	0	240	92.35	24.20	26.13
12	0	288	95.42	25.04	27.03
14	0	336	97.25	25.48	27.51
16	0	384	98.36	25.87	27.93
18	0	432	99.02	26.00	28.00
20	0	480	99.41	26.15	28.14
25	0	600	99.94	26.17	28.16
30	0	720	99.96	26.19	28.18
∞	0	∞	100.00	26.30	28.30

The same problem can be solved using Table 6 in the following manner:

In 7 days the cumulative dose per initial mCi of ^{198}Au is 23.62 mg · h. The number of mCi of ^{198}Au required for a cumulative dose of 1 410 mg · h is given by:

$$\frac{1\,410 \text{ mg} \cdot \text{h}}{23.62 \text{ mg} \cdot \text{h/mCi}} = 59.69 \text{ mCi of } ^{198}\text{Au}.$$

Discussion

In this paper the values for $\mu_{en(\text{air})_i}$, used in Table 3 have been obtained by multiplying the mass energy absorption coefficients in air, given by EVANS (1968) which are the best available, with the density of air and by interpolation.

These values can also be obtained from Radiological health handbook (1970). The value of Γ, obtained in the present work, which includes the contribution from bremsstrahlung is 2.49 R · cm²/mCi · h.

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SUMMARY

Two errors have been discussed in the dosimetry of ^{198}Au mould and implant therapy. The first one which leads to an overestimation of the dose by 8 % is due to the specific gamma-ray constant, Γ, which has different values in the literature varying from 2.19 to 2.43 R · cm²/mCi · h. Hence, the value of Γ for ^{198} Au was calculated from the first principles and found to be 2.49 R · cm²/mCi · h, which is different from the values given by the National Bureau of Standards (USA) and the National Research Council of Canada, as they did not include the contribution from bremsstrahlung. The second one which varies inversely with the treatment time, arises from the equivalence of 1 mCi of radon to 5.0 mCi (4.70 mCi—present work) of ^{198}Au. This equivalence is true only when both radon and ^{198}Au decay completely. When treatment time is considerably short (1 week) as in the case of moulds and removable implants, then the equivalent value of ^{198}Au in mCi should be multiplied by a factor which is the ratio of the percentage of radon decayed in one week to the percentage of ^{198}Au decayed in one week. In order to simplify the calculations and avoid the above errors a table has been prepared which directly gives the percentage decay of ^{198}Au in any specific period of time and the corresponding cumulative dose in mg · h of radium equivalent.

ZUSAMMENFASSUNG

Zwei Fehler bei der Dosimetrie der ^{198}Au-Form- und Implantationstherapie werden besprochen. Der erste, der die Dosis um 8 % zu hoch berechnet, beruht auf der spezifischen Konstante Γ der Gamma-Strahlung, für die in der Literatur verschiedene Werte zwischen 2,19 und 2,34 R · cm²/mCi · h angegeben sind. Deshalb wurde der Wert von Γ für ^{198}Au nach den ersten Grundsätzen bestimmt. Es wurde ein Wert von 2,49 R · cm²/mCi · h gefunden, der sich von denen, die das National Bureau of Standards (USA) und das National Research Council of Canada angegeben haben, unterscheidet, da diese nicht den Beitrag der Bremsstrahlung berücksichtigt haben. Der zweite Fehler, der sich umgekehrt mit der Behandlungszeit verändert, ergibt sich aus dem Äquivalent von 1 mCi Radon zu 5,0 mCi (4,70 mCi in der vorliegenden Arbeit) ^{198}Au. Dieses Äquivalent ist nur dann wirklich vorhanden, wenn sowohl der Radon- als auch der ^{198}Au-Zerfall vollständig ist. Wenn die Behandlungszeit beträchtlich kurz ist (1 Woche), wie es der Fall bei Formen und entfernbaren Implantaten der Fall ist, muss der Wert für das Äquivalent von ^{198}Au in mCi mit

einem Faktor multipliziert werden, der sich aus dem Verhältnis des prozentuellen ^{198}Au-Zerfalls einer Woche ergibt. Um die Berechnungen zu erleichtern und um die obengenannten Fehler zu vermeiden, ist eine Tabelle hergestellt worden, aus der sich der prozentuelle Abfall von ^{198}Au für jede spezifische Zeitperiode und die entsprechende kumulative Dosis in mg · h des Radiumäquivalents ergibt.

RÉSUMÉ

L'auteur a étudié deux erreurs dans la dosimétrie de ^{198} Au utilisé en moulage et en implantation. La première erreur qui surestime la dose de 8 % est due à la constante spécifique de rayonnement gamma, Γ, qui a des valeurs différentes dans la littérature allant de 2,19 à 2,34 R · cm^2/mCi · h. C'est pourquoi la valeur de Γ pour ^{198}Au a été calculée à partir des principes fondamentaux et trouvée égale à 2,49 R · cm^2/mCi · h, de qui est différent des valeurs données par le National Bureau of Standards (USA) et le National Research Council of Canada, étant donné qu'ils n'ont pas inclu la contribution du rayonnement de freinage. La seconde erreur qui varie en sens inverse de la durée du traitement provient de l'équivalence de 1 mCi de radon à 5,0 mCi (4,70 mCi — travail de l'auteur) de ^{198}Au. Cette équivalence n'est vraie que quand le Radon et ^{198}Au se désintègrent complètement. Qand le temps de traitement est très court (une semaine) comme dans le cas de moulage et d'implant provisoire, cette valeur équivalente de ^{198}Au en mCi devrait être multipliée par un facteur qui est le rapport du pourcentage de radon détruit en une semaine au pourcentage de ^{198}Au détruit en une semaine. Pour simplifier les calculs et pour éviter les erreurs mentionnées ci-dessus, l'auteur a établi une table qui donne directement le pourcentage de destruction de ^{198}Au dans les diverses périodes de temps et la dose cumulative correspondante en mg · h d'équivalent de radium.

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