THE YIELDS OF CYCLOTRON-PRODUCED RADIOISOTOPES FOR MEDICAL PURPOSES

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SUMMARY

The yields of most medical radioisotopes, produced with cyclotrons of various sizes through different nuclear reactions in laboratories around the world, and reported in literature since 1980, are presented. This compilation, combined with our previous publications (covering published data up until 1980)[1,2] would form a comprehensive collection of yields of cyclotron-produced medical radioisotopes. It would greatly help in selecting the most suitable nuclear reaction, and irradiation conditions, for producing a particular isotope. Such a compilation would also be useful in assessing various losses of isotopes during handling and chemical processing of the irradiated target.

INTRODUCTION

Production of radioisotopes for medical use is by far the most widely used and profitable application of cyclotrons. Presently, many isotopes are being produced by cyclotrons around the world for research and routine work in fields like nuclear medicine, nuclear biology, etc. Generally, neutron-deficient carrier-free and short-lived isotopes, which cannot be conveniently or at all produced with a reactor, are produced with cyclotrons. However, at the same time, neutron-enriched isotopes can also be produced with a cyclotron, if required, through nuclear reactions of the type (d,p), (^{3}He,p), (α,p), etc.

In our previous publications we presented the yields of many cyclotron-produced isotopes of medical interest, which were reported in the literature until 1980.[1,2]

In the present paper, we have considered some of those publications which have appeared since 1980. These, combined with our previous publications, should provide a comprehensive compilation of the yields of cyclotron-produced medical radioisotopes, and help in choosing the most suitable method for producing a particular isotope.

METHODS AND RESULTS

The production mode and respective yields of radio-isotopes at different energies, and from various targets, are summarized in Table 1. The yield figures given in the table are either actually obtained production yields or those calculated by authors from experimentally measured excitation functions.

In compiling the table, attempts have been made to include most of the significant published data, since 1980, regarding the production of various isotopes for biomedical applications. However, it is possible that some publications might have been inadvertently omitted.

The actual production cost of any particular isotope, dollars per millicurie, can be easily estimated from the yield figures, the running cost of the accelerator, the cost of the materials and the man-hours involved in the production and subsequent chemical processing (which can be seen from respective references). When one does these calculations one finds that, in most cases, the actual cost of producing an isotope is much less than that charged by the commercial organizations.

TABLE I

THE PRODUCTION MODES AND YIELDS OF SOME CYCLOTRON-PRODUCED ISOTOPES

T½ - half-life : m - minutes : h - hours : d - days

M - experimentally measured yields at the end of the bombardment E.O.B.

C - calculated yields using experimentally measured excitation functions

S.B. - saturation bombardment (bombardment duration of at least 4-5 times the half-life of the isotope being produced)

M.S.B. and C.S.B. - measurements and calculations at saturation bombardment

Isotope	T½	Reaction	Target Material	Bombarding Energy (MeV) IN - OUT	Production Yield (a) mCi/μA (b) mCi/μAh	Remarks	Ref
^{11}C (as HCN)	20.4m	$^{14}N(p,\alpha)$	N_2 - 94.5% H_2 5.5%	18	140 (a)	M.S.B.	3

TABLE I (cont'd)

Isotope	T½	Reaction	Target Material	Bombarding Energy (MeV) IN - OUT	Production Yield (a) mCi/μA (b) mCi/μAh	Remarks	Ref.
^{13}N	9.96m	^{16}O (p,α)	Circulating H_2O target	20	500 mCi of ^{13}N in 50 ml at 20 μA		4
		"	H_2O	14	35.8 (a)	M.S.B.	5
^{14}O	1.18m	^{14}N(p,α)	^{14}N	8	0.7 (a)	C.S.B.	6
		"	"	10	2.4 (a)	C.S.B.	6
^{15}O	2.04m	^{14}N (d,n)	$^{14}N_2$	6	32 (a)	C.S.B.	6
		"	"	8	50 (a)	C.S.B.	6
			$^{14}N_2$ with 5% H_2	10	72 (a)	C.S.B.	7
			$^{14}N_2$ with 2% O_2	10.2	57 (a)	C.S.B.	7
		^{15}N (p,n)	$^{15}N_2$	6	15 (a)	C.S.B.	6
		"	"	8	47 (a)	C.S.B.	6
		"	"	10	69 (a)	C.S.B.	6
		^{16}O (p,pn)	O_2	29	30 (a)	M.S.B.	8
^{18}F	1.83h	^{16}O (^3He,p) + ^{16}O (^3He,pn)	Water	36	10 (b)	M	9
		^{18}O (p,n)	$^{18}O_2$ (thick)	10	150 (a)	M.S.B.	10
			$H_2{}^{18}O$ (99% enriched)	10	47 (b)	M	9
				14	216 (a)	C.S.B.	11
			"	11 - 3	60 (b)	C	12
			"	16 - 3	80 (b)	C	12
			"	16.5 - 4	180 (a)	C.S.B.	13
			"	15/16	156 (b)	M	14
			"	"	170 (a)	M.S.B.	14
			"	15	43.2 (b)	M	15
		^{22}Ne(d,α)	$^{20}Ne_2$	9.4	67 (a)	M.S.B.	16
			"	14.0	82 (a)	M.S.B.	16
			$^{20}Ne_2$ (with 0.09-5% F_2)	14	17 (b)	M	17
			$^{20}Ne_2$ + F2	14 - 2	28 (b)	C	12
			$^{20}Ne_2$ + H2	8 - 2	17 (b)	C	12
		^{20}Ne(p,2pn)	Ne_2 natural	40	40 (a)	M.S.B.	8
^{28}Mg	21.1h	Proton spallation	KCl pressed pellet 0.8 cm thick in stainless steel container	191	0.0051 (b) (98 mCi/μg specific activity at E.O.B.)	M.S.B.	18

TABLE I (cont'd)

Isotope	T½	Reaction	Target Material	Bombarding Energy (MeV) IN - OUT	Production Yield mCi/µA (a) mCi/µAh (b)	Remarks	Ref.
^{30}P	2.5m	^{27}Al (α,n)	High purity Al	28	2 (b)	M	19
				"	4.6 (b)	C	19
^{34m}Cl	32m	^{34}S (p,n)	H_2S nat.	22	0.35 (b)	M	20
		^{34}S (d,n)	"	12	0.015 (b)	M	20
^{38}K	7.6m	^{35}Cl (α,n)	NaCl solid	14.7	0.6 (a)	M.S.B. (average of 21 runs)	21
		^{40}Ca (d,α)	CaO solid	7.8	0.28 (a)	M.S.B.	21
^{52}Mn	5.6d	^{52}Cr (p,n)	Natural Cr	10	0.035 (b)	M 24h post-irradiation	22
^{52m}Mn	21.1m	^{52}Cr (p,n)	" "	10	40 (a)	M.S.B.	22
^{55}Co	18.2h	^{54}Fe (d,n)	$^{54}Fe_2O_3$ (97.1% enriched)	12 - 6	1.725 (b)	C	23
					1.692 (b)	M	23
^{57}Co	271d	From ^{57}Ni	-	-	0.0022(b)	C 272h post-irradiation	24
^{57}Ni	36h	^{59}Co (p,3n)	Cobalt Metal	40	0.42 (b)	C	24
^{67}Cu	62.01h	^{68}Zn (p,2p) +	Nat. Zn	200	0.0042(a) per mg/cm^2	C	25
		^{70}Zn (p,α)			0.0033(a) per mg/cm^2	M	25
^{62}Zn	9.13h	^{63}Cu (p,2n)	Nat. Cu	26	3 (b)	M	26
^{63}Zn	38.1m	^{63}Cu (p,n)	Nat. Cu	15	125 (a)	M	27
^{67}Ga	3.24d	^{67}Zn (p,n)	^{67}Zn enriched foil	16 - 6	3.75 (b)	C	28
			"	18 - 6	4.18 (b)	C	28
			"	20 - 6	4.54 (b)	C	28
			"	18 - 6	40.0 (a)	C for 10h bombardment	28
			"	20 - 6	43.4 (a)	"	28
		^{68}Zn (p,2n)	^{68}Zn foil enriched	26 - 15	4.79 (b)	C	28
			"	28 - 15	5.61 (b)	C	28
			"	30 - 15	6.28 (b)	C	28
			"	26 - 15	45.8 (a)	C for 10h bombardment	28
			"	28 - 15	53.7 (a)	"	28
			"	30 - 15	60.1 (a)	"	28
		Zn (p,xn)	Natural Zn	26 - 15	0.86 (b)	C	28
				28 - 15	1.03 (b)	C	28
				30 - 15	1.18 (b)	C	28
^{68}Ga	68.1m	Produced from a ^{68}Ge - Generator					
^{68}Ge	287d	Ge (p,pxn)	99.9% pure Ge	64 - 28	0.048 (b)	M	29

TABLE I (cont'd)

Isotope	T½	Reaction	Target Material	Bombarding Energy (MeV) IN - OUT	Production Yield (a) - mCi/μA (b) - mCi/μAh	Remarks	Ref.
		^{69}Ga (p,2n)	Ga$_4$ Ni Alloy (80% Ga)	19.5	0.0092 (b) 0.013 (b)	M C	30
^{75}Br	1.7h	^{75}As (^{3}He,3n)	Cu$_3$ As Alloy (As - 31% Cu - 69%)	36 - 25 optimum energy range	1.5 (b)	M	31
				"	8.0 (b)	C	32
				"	7.5 (b)	C	12
		^{76}Se (p,2n)	^{76}Se (96.5%)	24 - 21.5	32.5 (b)	C	33
			"	30 - 22 optimum energy range	100 (b)	C	12
			^{76}Se (92.4%)	28 - 22	118 (b)	M	33
			Cu$_2$ ^{76}Se (92.4%)	"	43 (b)	M	33
		Br(d,xn)^{75}Kr - ^{75}Br	Na Br	90 - 68	0.21 (a)	M 8.5m irradiation, chemical processing, 8m growing-in time	32
^{76}Br	16.1h	^{75}As (^{3}He,2n)	Cu$_3$ As	18 - 10	0.30 (b)	M	12
		"	As	30	0.7 (b)	M	33
		^{76}Se (p,n)	^{76}Se(96.5%)	10	1 (b)	M	12
		"	"	16 - 10	8 (b)	M	12
		^{77}Se (p,2n)	^{77}Se (92.4%) in Na-Selenate	25 - 16	7.0 (b)	M	12
^{77}Br	57.0h	^{75}As (α,2n)	Cu$_3$ As Alloy	28 - 14	0.09 (b)	M	31
			(As - 31% Cu - 69%)	"	0.13 (b)	C	31
			As$_2$O$_3$	"	0.49 (b)	M	33
			"	28 - 21	0.162 (b)	M	33
		^{77}Se (p,n)	^{77}Se enriched	10	Ca. 0.2 (b)	C	12
		"	"	16	1.5 (b)	C	12
		"	" (94.4%)	12	0.51 (b)	M	33
		"	" (98.6%)	26	0.97 (b)	M	33
		^{78}Se (p,2n)	^{78}Se enriched	16	0.2 (b)	C	12
			Cu$_2$ ^{78}Se (^{78}Se - 97.9%)	25 - 20	4.32 (b)	M	33
^{77}Kr	1.2h	^{76}Se (^{3}He,2n)	^{76}Se (96.9% enriched)	25 - 15	7.5 (b)	C	34
		"	"	36 - 15	11.34 (b)	C	34
		^{77}Se (^{3}He,3n)	^{77}Se (94.4%)	36 - 15	11.5 (b)	C	34
		"	"	36 - 22	4 (b)	M	35
		Se (^{3}He,xn)	Nat. Se	36 - 15	1.56 (b)	M	34
		^{79}Be (p,3n) + ^{81}Br (p,5n)	Na Br (Nat. Br)	45 - 32	62.8 (b)	C	36

TABLE I (cont'd)

Isotope	T½	Reaction	Target Material	Bombarding Energy (MeV) IN - OUT	Production Yield (a) - mCi/μA (b) - mCi/μAh	Remarks	Ref.
^{79}Kr	35h	^{79}Br (p,n) + ^{81}Br (p,3n)	Na Br (Nat. Br)	45 - 0	14.9 (b)	C	36
^{81}Rb	4.7h	Kr (p,xn)	Natural Kr gas	20	0.8 (b)	C	37
		"	"	26	1.0 (b)	C	37
^{82m}Rb	6.4h	Kr (p,xn)	Nat. Kr gas	20	0.7 (b)	C	37
		"	"	26	0.85 (b)	C	37
^{87}Y	80h	^{88}Sr (p,2n)	Sr metal	22 - 0	2.34 (b)	M (E.O.B. + 50h)	38
		"	"	26 - 20	2.74 (b)	M (E.O.B. + 30h)	38
		"	Sr Cl$_2$	26 - 20	0.7 (b)	M (E.O.B. + 30h)	38
		Sr (d,xn)	Sr metal	22 - 0	0.51 (b)	M (E.O.B. + 50h)	38
^{92}Tc	4.4m	^{92}Mo (p,n)	^{92}Mo - oxide (99.4% enriched)	15	0.075 (a) per mg/cm^2	M.S.B.	39
^{97}Ru	2.88d	^{103}Rh (p,xn)	Rh metal	67.5 - 37	1.36 (b)	M	40
^{101m}Rh	4.3d	^{103}Rh(p,3n)^{101}Pd - ^{101m}Rh	"	67 - 15	4.7 (b)	M (E.O.B. + 32.7h)	41
		^{103}Rh (p,p2n)	"	67 - 15	5.4 (b)	M	41
^{111g}In	2.83d	^{109}Ag (α,2n)	Nat. Ag	30	100 (b)	M	42
+				40	300 (b)	M	42
^{111m}In	7.73m			50	500 (b)	M	42
^{117m}Sn	14.0d	^{116}Cd (α,3n)	^{116}Cd (97%)	50 - 20	0.17 (b)	C	43
		^{115}In (α,pn+d)	Nat. In	45 - 20	0.009 (b)	C	43
^{122}Xe	20.1h	^{127}I (p,6n)	NaI (3.8g/cm^2)	67.5 - 45.8	5.6 (b)	M	44,45
^{122}I		Produced from a	^{122}Xe generator				
^{123}I	13.2h	^{123}Te (p,n)	^{123}Te enriched	10	0.1 (b)	C	12
		"	"	16	3.5 (b)	C	12
		^{124}Te (p,2n)	^{124}Te (99.97%)	22.4 - 20	6 (b)	C	46
			^{124}Te O$_2$ (99.97% enriched Te)	22.4 - 20	4 (b)	M	47
		^{122}Te (d,n)	^{122}Te (96.5% enriched Te)	8	Ca. 0.2 (b)	C	12
			"	12.7 - 6	0.5 (b)	M	46
			"	14 - 8	1.7 (b)	C	46

TABLE I (cont'd)

Isotope	T½	Reaction	Target Material	Bombarding Energy (MeV) IN - OUT	Production Yield (a) - mCi/μA (b) - mCi/μAh	Remarks	Ref.
		^{124}Xe (p,2n)^{123}Cs - ^{123}Xe - ^{123}I	^{124}Xe gas (99.9%)	16	Ca. 0.2 (b)	C	12
		+					
		^{124}Xe (p,pn)^{123}Xe		27 - 25	4.2 (b)	C	12
		- ^{123}I		30 - 25	Ca. 10 (b)	C	12
		^{127}I(p,5n)^{123}Xe - ^{123}I	NaI (Nat. I)	65 - 50	15 (b)	M (E.O.B. + 30h)	12
^{123}Xe	2.08h	^{127}I (p,5n)	NaI	67.5 - 45.8	197 (b)	M	44,45
^{128}Ba	2.42d	^{133}Cs (p,6n)	CsCl disc (2.3g/cm^2)	67 - 54 (optimum range)	3 (b)	M	48
^{128}Cs	3.6m	Produced from ^{128}Ba					
^{195m}Hg	41.3h	^{197}Au (p,3n)	Au (1 mm)	32	5.4 (b)	M	49
		"	Au	34 - 26	4.6 (b)	M	50
^{201}Pb	9.4h	^{203}Tl (p,3n)	^{203}Tl (97% enriched)	30	16.9 (b)	M	51
^{201}Tl	3.06d	Produced from ^{201}Pb					
^{211}At	7.21h	^{209}Bi (α,2n)	Bi-metal (99.9% pure)	27.7 - 22	4.37 (a)	M.S.B.	52
^{237}Pu	46d	^{237}Np (d,2n)	^{237}Np-oxide	15	0.0004 (b)	C	53
		"	"	25	0.0013 (b)	C	53

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