Medical Physics Data Book

NBS Handbook 138

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[1] Headquarters and Laboratories at Gaithersburg, MD, unless otherwise noted; mailing address Washington, DC 20234.
[2] Some divisions within the center are located at Boulder, CO 80303.

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PREFACE

For the past 3 years the Medical Physics Data Group of the American Association of Physicists in Medicine has worked with the Publications Committee to produce a source of reliable and readily accessible data for the practicing medical physicist. The Medical Physics Data Book is the result of that effort.

The contents are divided into five main chapters: General Physics, Nuclear Medicine, Diagnostic Radiology, Radiation Therapy, and Non-Ionizing Radiation. The editors have tried to selectively assemble the most useful information for each chapter while maintaining a text of manageable size. Each entry is referenced so the user can determine the original sources of data and the conditions under which they were assembled. An effort has also been made to present the material using consistent units and unit symbols throughout.

The editors wish to express their appreciation to all those who reviewed the manuscript and made useful comments. We are also grateful to Ms. Cynthia A. Goldman, Librarian, Office of Standard Reference Data, NBS, who coordinated the collection and production of photographs from the literature and verified the references. Appreciation is also extended to the NBS Electronic Typesetting staff for preparing the text for computerized photocomposition.

The user is cautioned to confirm the applicability of these data to specific needs as the American Association of Physicists in Medicine and the National Bureau of Standards assume no liability in the use of these data.

Corrections and suggestions for future editions of the Medical Physics Data Book should be brought to the attention of Dr. S. P. Fivozinsky at the National Bureau of Standards.

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Thomas N. Padikal, Ph. D.
Editor-in-Chief

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CHAPTER ONE: GENERAL PHYSICS

I. The Metric System of Measurement [1]

A. SI base units

The SI is constructed from seven base units for independent quantities plus two supplementary units for plane angle and solid angle.

Quantity	Name	Symbol
SI base units:		
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd
SI supplementary units:		
plane angle	radian	rad[a]
solid angle	steradian	sr

[a] See footnote, section IB.

B. SI derived units

	SI Unit		
Quantity	Name	Symbol	Expression in terms of other units
frequency	hertz	Hz	1/s
force	newton	N	$kg{\cdot}m/s^2$
pressure, stress	pascal	Pa	N/m^2
energy, work, quantity of heat	joule	J	N·m
power, radiant flux	watt	W	J/s
quantity of electricity, electric charge	coulomb	C	A·s
electric potential, potential difference, electromotive force	volt	V	W/A
capacitance	farad	F	C/V
electric resistance	ohm	Ω	V/A
conductance	siemens	S	A/V
magnetic flux	weber	Wb	V·s
magnetic flux density	tesla	T	Wb/m^2
inductance	henry	H	Wb/A
luminous flux	lumen	lm	cd·sr
illuminance	lux	lx	lm/m^2
activity (of ionizing radiation source)	becquerel	Bq	1/s
absorbed dose[a]	gray	Gy	J/kg

[a] Absorbed dose in rads (symbol, rd) is the most often utilized quantity. In this handbook rad is also used as the unit symbol, following common usage (10^{-2} Gy=1 rad). Note that rad is the accepted SI unit symbol for plane angle.

C. Multiplier prefixes for SI units

For use with the SI units there is a set of 16 prefixes to form multiples and submultiples of the units. It is important to note that the kilogram is the only SI base unit with a prefix. Because double prefixes are not to be used, the prefixes, in the case of mass, are to be used with gram (symbol g) and not with kilogram (symbol kg).

SI prefixes

Factor	Prefix	Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10^{1}	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

II. Conversion Tables [1]

A. Length

	cm	m	km	in	ft	mi
1 centimeter =	1	10^{-2}	10^{-5}	0.3937	3.281×10^{-2}	6.214×10^{-6}
1 METER =	100	1	10^{-3}	39.3	3.281	6.214×10^{-4}
1 kilometer =	10^{5}	1000	1	3.937×10^{4}	3281	0.6214
1 inch =	2.540	2.540×10^{-2}	2.540×10^{-5}	1	8.333×10^{-2}	1.578×10^{-5}
1 foot =	30.48	0.3048	3.048×10^{-4}	12	1	1.894×10^{-4}
1 mile =	1.609×10^{5}	1609	1.609	6.336×10^{4}	5280	1

1 angstrom $=10^{-10}$ m
1 nautical mile = 1852 m
= 1.151 miles = 6076 ft

1 light year $=9.4600\times10^{12}$ km
1 parsec $=3.084\times10^{13}$ km
1 fathom = 6 ft

1 yard = 3 ft
1 rod = 16.5 ft
1 mil $=10^{-3}$ in

B. Mass

	g	kg	oz	lb	ton
1 gram=	1	0.001	3.527×10^{-2}	2.205×10^{-3}	1.102×10^{-6}
1 KILOGRAM=	1000	1	35.27	2.205	1.102×10^{-3}
1 ounce=	28.35	2.835×10^{-2}	1	6.250×10^{-2}	3.125×10^{-5}
1 pound=	453.6	0.4536	16	1	0.0005
1 ton=	9.072×10^{5}	907.2	3.2×10^{4}	2000	1

C. Energy

	Btu	erg	ft·lb	hp·h	J	cal	kW·h	eV	MeV
1 British Thermal Unit=	1	1.055×10^{10}	777.9	3.929×10^{-4}	1055	252.0	2.930×10^{-4}	6.585×10^{21}	6.585×10^{15}
1 erg =	9.481×10^{-11}	1	7.376×10^{-8}	3.725×10^{-14}	10^{-7}	2.389×10^{-8}	2.778×10^{-14}	6.242×10^{11}	6.242×10^{5}
1 foot-pound=	1.285×10^{-3}	1.356×10^{7}	1	5.051×10^{-7}	1.356	.3239	3.766×10^{-7}	8.464×10^{18}	8.464×10^{12}
1 horsepower-hour=	2545	2.685×10^{13}	1.980×10^{6}	1	2.685×10^{6}	6.414×10^{5}	.7457	1.676×10^{25}	1.676×10^{19}
1 JOULE=	9.481×10^{-4}	10^{7}	.7376	3.725×10^{-7}	1	.2389	2.778×10^{-7}	6.242×10^{18}	6.242×10^{12}
1 calorie=	3.968×10^{-3}	4.186×10^{7}	3.087	1.559×10^{-6}	4.186	1	1.163×10^{-6}	2.613×10^{19}	2.613×10^{13}
1 kilowatt-hour=	3413	3.6×10^{13}	2.655×10^{6}	1.341	3.6×10^{6}	8.601×10^{5}	1	2.247×10^{25}	2.247×10^{19}
1 electron volt=	1.519×10^{-22}	1.602×10^{-12}	1.182×10^{-19}	5.967×10^{-26}	1.602×10^{-19}	3.827×10^{-20}	4.450×10^{-26}	1	10^{-6}
1 Mega electron volt=	1.519×10^{-16}	1.602×10^{-6}	1.182×10^{-13}	5.967×10^{-20}	1.602×10^{-13}	3.827×10^{-14}	4.450×10^{-20}	10^{6}	1

D. Power

	Btu/h	ft·lb/s	hp	cal/s	kW	W
1 British thermal unit/h=	1	0.2161	3.929×10^{-4}	7.000×10^{-2}	2.930×10^{-4}	0.2930
1 foot-pound/s=	4.628	1	1.818×10^{-3}	0.3239	1.356×10^{-3}	1.356
1 horsepower=	2545	550	1	178.2	0.7457	745.7
1 calorie/s=	14.29	3.087	5.613×10^{-3}	1	4.186×10^{-3}	4.186
1 kilowatt=	3413	737.6	1.341	238.9	1	1000
1 WATT=	3.413	0.7376	1.341×10^{-3}	0.2389	0.001	1

E. Time

	y	d	h	min	s
1 year=	1	365.2	8.766×10^{3}	5.259×10^{5}	3.156×10^{7}
1 day=	2.738×10^{-3}	1	24	1440	8.640×10^{4}
1 hour=	1.141×10^{-4}	4.167×10^{-2}	1	60	3600
1 minute=	1.901×10^{-6}	6.944×10^{-4}	1.667×10^{-2}	1	60
1 SECOND=	3.169×10^{-8}	1.157×10^{-5}	2.778×10^{-4}	1.667×10^{-2}	1

F. Force

	dyne	N	lb
1 dyne =	1	10^{-5}	2.248×10^{-6}
1 NEWTON =	10^{5}	1	0.2248
1 pound =	4.448×10^{5}	4.448	1

G. Pressure

	atm	dyne/cm²	inch of water	cm Hg	Pa	lb/in²	lb/ft²
1 atmosphere =	1	1.013×10^{6}	406.8	76	1.013×10^{5}	14.70	2116
1 dyne/cm² =	9.869×10^{-7}	1	4.015×10^{-4}	7.501×10^{-5}	0.1	1.450×10^{-5}	2.089×10^{-3}
1 inch of water[a] at 4 °C =	2.458×10^{-3}	2491	1	0.1868	249.1	3.613×10^{-2}	5.202
1 centimeter of mercury[a] at 0 °C =	1.316×10^{-2}	1.333×10^{4}	5.353	1	1333	0.1934	27.85
1 PASCAL =	9.869×10^{-6}	10	4.015×10^{-3}	7.501×10^{-4}	1	1.450×10^{-4}	2.089×10^{-2}
1 pound/in² =	6.805×10^{-2}	6.895×10^{4}	27.68	5.171	6.895×10^{3}	1	144
1 pound/ft² =	4.725×10^{-4}	478.8	0.1922	3.591×10^{-2}	47.88	6.944×10^{-3}	1

[a] Where the acceleration of gravity has the standard value 9.80665 m/s².

III. Physical Constants [2,3]

		Uncertainty (ppm)
Avogadro Number, N	$= 6.022045 \times 10^{23}$/mol	5.1
Velocity of light in vacuum, c	$= 2.99792458 \times 10^{8}$ m/s	0.004
Elementary Charge, e	$= 1.6021892 \times 10^{-19}$ C	2.9
Planck Constant	$= 6.626176 \times 10^{-34}$ J·s	2.6
Boltzmann Constant, k	$= 8.61735 \times 10^{-11}$ MeV/K	31.0
Molar Gas Constant, R	= 8.31441 J/(mol·K)	31.0
Density of dry air (at 20 °C, 760 mm Hg)	$= 1.205 \times 10^{-3}$ g/cm³	
Velocity of sound in air (10 °C, 760 mm Hg)	= 331.4 m/s	

IV. Periodic Table of the Elements

The number above the symbol is the atomic weight, the numbers below are the atomic number and the density in g/cm^3 at room temperature (20 °C).

I	II	III	IV	V	VI	VII	VIII		
1.01 H 1 0.0001									4.00 He 2 0.0002
6.94 Li 3 0.5	9.01 Be 4 1.8	10.81 B 5 2.5	12.01 C 6 2.3/3.5	14.01 N 7 0.0013	16.00 O 8 0.0014	19.00 F 9 0.0017			20.18 Ne 10 0.0009
22.99 Na 11 1.0	24.31 Mg 12 1.7	26.98 Al 13 2.7	28.09 Si 14 2.4	30.97 P 15 1.8/2.3	32.06 S 16 2.0/2.1	35.45 Cl 17 0.0032			39.95 Ar 18 0.0018
39.10 K 19 0.9	40.08 Ca 20 1.6	44.96 Sc 21 2.5	47.88 Ti 22 4.5	50.94 V 23 6.0	52.00 Cr 24 7.1	54.94 Mn 25 7.4	55.85 Fe 26 7.9	58.93 Co 27 8.9	58.69 Ni 28 8.9
63.55 Cu 29 8.9	65.38 Zn 30 7.1	69.72 Ga 31 5.9	72.59 Ge 32 5.9	74.92 As 33 5.7	78.96 Se 34 4.5/4.8	79.90 Br 35 3.1			83.80 Kr 36 0.0037
85.47 Rb 37 1.5	87.62 Sr 38 2.6	88.91 Y 39 5.5	91.22 Zr 40 6.5	92.91 Nb 41 8.5	95.94 Mo 42 10.2	(98) Tc 43 11.5	101.1 Ru 44 12.3	102.9 Rh 45 12.5	106.4 Pd 46 12.0
107.9 Ag 47 10.5	112.4 Cd 48 8.6	114.8 In 49 7.3	118.7 Sn 50 5.8/7.3	121.8 Sb 51 6.7	127.6 Te 52 6.2	126.9 I 53 4.9			131.3 Xe 54 0.0059
132.9 Cs 55 1.9	137.3 Ba 56 3.5	1)	178.5 Hf 72 13.3	180.9 Ta 73 16.6	183.9 W 74 19.3	186.2 Re 75 20.5	190.2 Os 76 22.5	192.2 Ir 77 22.4	195.1 Pt 78 21.4
197.0 Au 79 19.3	200.6 Hg 80 13.5	204.4 Tl 81 11.8	207.2 Pb 82 11.3	209.0 Bi 83 9.8	(209) Po 84 9.2	(210) At 85			(222) Rn 86 0.0099
(223) Fr 87	226.0 Ra 88 5.0	2)	(261) Unq 104	(262) Unp 105	(263) Unh 106				
1) Lanthanides:			138.9 La 57 6.2	140.1 Ce 58 6.8	140.9 Pr 59 6.5	144.2 Nd 60 6.9	(145) Pm 61	150.4 Sm 62 7.7	152.0 Eu 63 5.2
		157.3 Gd 64 7.9	158.9 Tb 65 8.3	162.5 Dy 66 8.6	164.9 Ho 67 10.1	167.3 Er 68 9.1	168.9 Tm 69 9.3	173.0 Yb 70 7.0	175.0 Lu 71 9.7
2) Actinides:			227.0 Ac 89	232.0 Th 90 11.6	231.0 Pa 91 15.4	238.0 U 92 18.7	237.0 Np 93	(244) Pu 94	(243) Am 95
		(247) Cm 96	(247) Bk 97	(251) Cf 98	(252) Es 99	(257) Fm 100	(258) Md 101	(258) No 102	(260) Lr 103

V. Properties of Some of the Elementary Particles [3]

Family name	Particle name	Rest mass (MeV)	Mean life (seconds)	Charge (electron)	Typical decay mode
	Photon (γ)	0	Stable	0	
LEPTONS	Electron (e)	0.511	Stable	± 1	
LEPTONS	Muon (μ)	105.7	2.197×10^{-6}	± 1	$e + \nu + \bar{\nu}$
LEPTONS	Electron's neutrino (ν_e)	0	Stable	0	
LEPTONS	Muon's neutrino (ν_μ)	0	Stable	0	
HADRONS, MESONS	Pion (π)	139.6	2.603×10^{-8}	± 1	$\mu + \nu$
HADRONS, MESONS	(π^0)	135.0	8.28×10^{-17}	0	$\gamma + \gamma$
HADRONS, MESONS	K-meson (K)	493.7	1.237×10^{-8}	± 1	$\mu + \nu$
HADRONS, MESONS	(K^0)	497.7	8.930×10^{-11}	0	$\pi^+ + \pi^-$
			5.181×10^{-8}	0	$\pi^0 + \pi^0 + \pi^0$
HADRONS	Eta-meson (η^0)	548.8	?	0	$\gamma + \gamma$
HADRONS, BARYONS, NUCLEON	Proton (p)	938.3	Stable	± 1	
HADRONS, BARYONS, NUCLEON	Neutron (n)	939.6	918	0	$p + e^- + \nu$
HADRONS, BARYONS	Lambda particle (Λ^0)	1116	2.578×10^{-10}	0	$p + \pi^-$
HADRONS, BARYONS	Sigma particle (Σ^+)	1189	8.00×10^{-11}	± 1	$p + \pi^0$
HADRONS, BARYONS	(Σ^0)	1192	$< 1.0 \times 10^{-14}$	0	$\Lambda^0 + \gamma$
HADRONS, BARYONS	(Σ^-)	1197	1.482×10^{-10}	∓ 1	$n + \pi^-$
HADRONS, BARYONS	Xi particle (Ξ^0)	1315	2.96×10^{-10}	0	$\Lambda^0 + \pi^0$
HADRONS, BARYONS	(Ξ^-)	1321	1.652×10^{-10}	∓ 1	$\Lambda^0 + \pi^-$
HADRONS, BARYONS	Omega particle (Ω^-)	1672	1.3×10^{-10}	∓ 1	$\Xi^0 + \pi^-$

VI. Binding Energies of Electronic Shells of Selected Elements [4]

Atomic number	Element	Binding energy of shell (keV)			
		K	L_{I}	L_{II}	L_{III}
1	Hydrogen	0.0136			
6	Carbon	0.283			
8	Oxygen	0.531			
11	Sodium	1.08	0.055	0.034	0.034
13	Aluminum	1.559	0.087	0.073	0.072
14	Silicon	1.838	0.118	0.099	0.098
19	Potassium	3.607	0.341	0.297	0.294
20	Calcium	4.038	0.399	0.352	0.349
26	Iron	7.111	0.849	0.721	0.708
29	Copper	8.980	1.100	0.953	0.933
31	Gallium	10.368	1.30	1.134	1.117
32	Germanium	11.103	1.42	1.248	1.217
39	Yttrium	17.037	2.369	2.154	2.079
42	Molybdenum	20,002	2.884	2.627	2.523
47	Silver	25.517	3.810	3.528	3.352
53	Iodine	33.164	5.190	4.856	4.559
54	Xenon	34.570	5.452	5.104	4.782
56	Barium	37.410	5.995	5.623	5.247
57	Lanthanum	38.931	6.283	5.894	5.489
58	Cerium	40.449	6.561	6.165	5.729
74	Tungsten	69.508	12.090	11.535	10.198
79	Gold	80.713	14.353	13.733	11.919
82	Lead	88.001	15.870	15.207	13.044
92	Uranium	115.591	21.753	20.943	17.163

VII. Photon Fluence, Energy Fluence, and Mass Energy-Absorption Coefficient as a Function of Photon Energy [5]

Photon energy (MeV)	Photon fluence Φ/X (photons/(m^2·R))	Energy fluence Ψ/X (J/(m^2·R))	Mass energy absorption coefficient $(\mu_{en}/\rho)_{air}$ (cm^2/g)
0.010	$11.7\cdot10^{12}$	$18.7\cdot10^{-3}$	4.66
0.015	$28.1\cdot10^{12}$	$67.4\cdot10^{-3}$	1.29
0.020	$52.6\cdot10^{12}$	$169\cdot10^{-3}$	0.516
0.030	$123\cdot10^{12}$	$591\cdot10^{-3}$	0.147
0.040	$212\cdot10^{12}$	$1360\cdot10^{-3}$	0.0640
0.050	$283\cdot10^{12}$	$2270\cdot10^{-3}$	0.0384
0.060	$310\cdot10^{12}$	$2980\cdot10^{-3}$	0.0292
0.080	$288\cdot10^{12}$	$3690\cdot10^{-3}$	0.0236
0.100	$235\cdot10^{12}$	$3770\cdot10^{-3}$	0.0231
0.15	$144\cdot10^{12}$	$3470\cdot10^{-3}$	0.0251
0.20	$101\cdot10^{12}$	$3250\cdot10^{-3}$	0.0268
0.30	$62.8\cdot10^{12}$	$3020\cdot10^{-3}$	0.0288
0.40	$45.9\cdot10^{12}$	$2940\cdot10^{-3}$	0.0296
0.50	$36.6\cdot10^{12}$	$2930\cdot10^{-3}$	0.0297
0.60	$30.6\cdot10^{12}$	$2940\cdot10^{-3}$	0.0296
0.80	$23.5\cdot10^{12}$	$3010\cdot10^{-3}$	0.0289
1.00	$19.4\cdot10^{12}$	$3110\cdot10^{-3}$	0.0280
1.50	$14.2\cdot10^{12}$	$3410\cdot10^{-3}$	0.0255
2.00	$11.6\cdot10^{12}$	$3720\cdot10^{-3}$	0.0234
5.00	$6.28\cdot10^{12}$	$5030\cdot10^{-3}$	0.0173
10.00	$3.77\cdot10^{12}$	$6040\cdot10^{-3}$	0.0144

$$\frac{\Phi}{X} = \frac{5.43\cdot10^{14}}{(\mu_{en}/\rho)_{air}\cdot(h\nu)} \text{ photons/(m}^2\text{·R), } h\nu \text{ is in keV.}$$

$$\frac{\Psi}{X} = \frac{86.9\cdot10^{-3}}{(\mu_{en}/\rho)_{air}} \text{ J/(m}^2\text{·R).}$$

VIII. Energy of *K*-edge and Fluorescent Yield as a Function of Atomic Number [6]

Energy E_K, of K x-rays, and ω_K the fluorescent yield is presented as a function of atomic number Z. The fluorescent yield is the number of K x-rays per hole in the K shell; $1-\omega_K$ is the number of Auger electrons emitted per K shell vacancy.

Z	E_K (MeV)	ω_K	Z	E_K (MeV)	ω_K
10	0.0009	All energy is locally absorbed	50	0.025	0.85
15	0.002		55	0.031	0.87
20	0.004	0.15			
25	0.006	0.27			
30	0.009	0.43	70	0.052	0.94
35	0.012	0.63			
40	0.016	0.70	80	0.071	0.95
45	0.020	0.80	92		0.97

General equation governing fluorescent yield:

$$\frac{\omega_K}{1-\omega_K} = ((-6.4 \cdot 10^{-2}) + (3.4 \cdot 10^{-2} \cdot Z) - (1.03 \cdot 10^{-6} \cdot Z^3))^4,$$

where Z is the atomic number.

IX. Mass Electron Density, Mass Density, Electron Density, and Effective Atomic Numbers for Selected Materials [7]

Material	N_g/N_A	ρ (g/cm^3)	$\rho\cdot(N_g/N_A)$	Z_R^a	Z_{PE}^a
Water (H_2O)	0.556	1.00	0.556[b]	7.16	7.54
Polyethylene (C_2H_4)	0.571	0.92	0.526	5.22	5.56
Polystyrene (C_8H_8)	0.538	1.05	0.565	5.57	5.76
Nylon ($C_6H_{11}NO$)	0.549	1.15	0.631	5.91	6.25
Lexan ($C_{16}H_{14}O_3$)	0.528	1.20	0.633	6.11	6.36
Plexiglas ($C_5H_8O_2$)	0.540	1.19	0.643	6.25	6.60
Bakelite ($C_{43}H_{38}O_7$)	0.529	1.34	0.708	6.06	6.31
Teflon (C_2F_4)	0.480	2.20	1.056	8.35	8.50
Brain	0.551[b]	1.03[c]	0.567[b]	7.01[b]	7.60[b]
Muscle	0.551	1.04	0.573	7.12	7.72
Kidney	0.540	1.05	0.567	7.19	7.76
Liver	0.555	1.05	0.583	7.24	7.81

[a] Based on exponents of 2.0 and 3.8 for coherent (R) and photoelectric (PE) interactions, respectively, e.g.: Z_{PE} for water$=((8/10)\,8^{3.8}+(2/10)1^{3.8})^{1/3.8}$.

[b] Values for biological materials based on weight fractions given in section XII of this chapter.

[c] Values given are from work of Rao and Gregg [8] and should be taken as "representative."

N_A is the Avogadro number, N_g is the mass electron density ($N_g=N_A\cdot(\overline{Z/A})$=electrons per gram) and ρN_g is the electron density in electrons/cm^3. The effective Z/A, is computed from $\overline{Z/A}=\Sigma\, W_i\,(Z_i/A_i)$ where W_i is the weight fraction of the i-th constituent. ρ is the mass density.

X. Mass Attenuation Coefficients of Selected Materials at Selected Energies [9]

PHOTON ENERGY	ALUMINUM $Z=13$	SILICON $Z=14$	PHOSPHORUS $Z=15$	SULFUR $Z=16$	ARGON $Z=18$	POTASSIUM $Z=19$	CALCIUM $Z=20$	IRON $Z=26$
Mev				*cm²/g*				
1.00 − 02	2.58 + 01	3.36 + 01	4.02 + 01	5.03 + 01	6.38 + 01	8.01 + 01	9.56 + 01	1.72 + 02
1.50 − 02	7.66 + 00	9.97 + 00	1.20 + 01	1.52 + 01	1.95 + 01	2.46 + 01	2.96 + 01	5.57 + 01
2.00 − 02	3.24 + 00	4.19 + 00	5.10 + 00	6.42 + 00	8.27 + 00	1.05 + 01	1.26 + 01	2.51 + 01
3.00 − 02	1.03 + 00	1.31 + 00	1.55 + 00	1.94 + 00	2.48 + 00	3.14 + 00	3.82 + 00	7.88 + 00
4.00 − 02	5.14 − 01	6.35 − 01	7.31 − 01	8.91 − 01	1.11 + 00	1.39 + 00	1.67 + 00	3.46 + 00
5.00 − 02	3.34 − 01	3.96 − 01	4.44 − 01	5.27 − 01	6.30 − 01	7.77 − 01	9.25 − 01	1.84 + 00
6.00 − 02	2.55 − 01	2.92 − 01	3.18 − 01	3.67 − 01	4.20 − 01	5.12 − 01	5.95 − 01	1.13 + 00
8.00 − 02	1.89 − 01	2.07 − 01	2.15 − 01	2.38 − 01	2.52 − 01	2.96 − 01	3.34 − 01	5.50 − 01
1.00 − 01	1.62 − 01	1.73 − 01	1.75 − 01	1.89 − 01	1.89 − 01	2.16 − 01	2.37 − 01	3.42 − 01
1.50 − 01	1.34 − 01	1.40 − 01	1.38 − 01	1.45 − 01	1.36 − 01	1.50 − 01	1.59 − 01	1.84 − 01
2.00 − 01	1.20 − 01	1.25 − 01	1.22 − 01	1.27 − 01	1.17 − 01	1.28 − 01	1.33 − 01	1.39 − 01
3.00 − 01	1.03 − 01	1.07 − 01	1.04 − 01	1.08 − 01	9.79 − 02	1.06 − 01	1.09 − 01	1.07 − 01
4.00 − 01	9.22 − 02	9.54 − 02	9.28 − 02	9.58 − 02	8.68 − 02	9.38 − 02	9.66 − 02	9.21 − 02
5.00 − 01	8.41 − 02	8.70 − 02	8.46 − 02	8.72 − 02	7.90 − 02	8.52 − 02	8.78 − 02	8.29 − 02
6.00 − 01	7.77 − 02	8.05 − 02	7.82 − 02	8.06 − 02	7.29 − 02	7.87 − 02	8.09 − 02	7.62 − 02
8.00 − 01	6.83 − 02	7.06 − 02	6.86 − 02	7.08 − 02	6.40 − 02	6.90 − 02	7.09 − 02	6.65 − 02
1.00 + 00	6.14 − 02	6.35 − 02	6.17 − 02	6.36 − 02	5.75 − 02	6.20 − 02	6.37 − 02	5.96 − 02
1.50 + 00	5.00 − 02	5.18 − 02	5.03 − 02	5.19 − 02	4.69 − 02	5.06 − 02	5.20 − 02	4.87 − 02
2.00 + 00	4.32 − 02	4.48 − 02	4.36 − 02	4.49 − 02	4.07 − 02	4.39 − 02	4.52 − 02	4.25 − 02
3.00 + 00	3.54 − 02	3.68 − 02	3.59 − 02	3.71 − 02	3.38 − 02	3.66 − 02	3.78 − 02	3.62 − 02
4.00 + 00	3.11 − 02	3.24 − 02	3.17 − 02	3.29 − 02	3.02 − 02	3.28 − 02	3.40 − 02	3.31 − 02
5.00 + 00	2.84 − 02	2.97 − 02	2.92 − 02	3.04 − 02	2.80 − 02	3.06 − 02	3.17 − 02	3.14 − 02
6.00 + 00	2.66 − 02	2.79 − 02	2.75 − 02	2.87 − 02	2.67 − 02	2.91 − 02	3.03 − 02	3.05 − 02
8.00 + 00	2.44 − 02	2.57 − 02	2.55 − 02	2.68 − 02	2.51 − 02	2.76 − 02	2.89 − 02	2.98 − 02
1.00 + 01	2.31 − 02	2.46 − 02	2.45 − 02	2.58 − 02	2.44 − 02	2.70 − 02	2.83 − 02	2.98 − 02
1.50 + 01	2.19 − 02	2.34 − 02	2.36 − 02	2.51 − 02	2.41 − 02	2.68 − 02	2.83 − 02	3.07 − 02
2.00 + 01	2.16 − 02	2.33 − 02	2.35 − 02	2.52 − 02	2.44 − 02	2.73 − 02	2.89 − 02	3.21 − 02
3.00 + 01	2.19 − 02	2.38 − 02	2.42 − 02	2.61 − 02	2.55 − 02	2.86 − 02	3.05 − 02	3.45 − 02

PHOTON ENERGY	COPPER $Z=29$	MOLYBDENUM $Z=42$	TIN $Z=50$	IODINE $Z=53$	TUNGSTEN $Z=74$	LEAD $Z=82$	URANIUM $Z=92$	ABSORPTION EDGES
Mev				*cm²/g*				
1.00 − 02	2.23 + 02	8.40 + 01	1.39 + 02	1.58 + 02	9.12 + 01	1.28 + 02	1.73 + 02	
1.50 − 02	7.33 + 01	2.68 + 01	4.53 + 01	5.34 + 01	1.39 + 02	1.12 + 02	6.03 + 01	L_{III} EDGE
2.00 − 02	3.30 + 01	1.17 + 01	2.02 + 01	2.47 + 01	6.51 + 01	8.34 + 01	6.85 + 01	L_{II}, L_{I} EDGES
3.00 − 02	1.06 + 01	2.83 + 01	4.07 + 01	7.98 + 00	2.18 + 01	2.84 + 01	3.96 + 01	
4.00 − 02	4.71 + 00	1.30 + 01	1.89 + 01	2.23 + 01	9.97 + 00	1.31 + 01	1.87 + 01	
5.00 − 02	2.50 + 00	6.97 + 00	1.04 + 01	1.23 + 01	5.40 + 00	7.22 + 00	1.04 + 01	
6.00 − 02	1.52 + 00	4.25 + 00	6.32 + 00	7.55 + 00	3.28 + 00	4.43 + 00	6.45 + 00	
8.00 − 02	7.18 − 01	1.92 + 00	2.90 + 00	3.52 + 00	7.66 + 00	2.07 + 00	3.04 + 00	
1.00 − 01	4.27 − 01	1.05 + 00	1.60 + 00	1.91 + 00	4.29 + 00	5.23 + 00	1.71 + 00	K EDGE
1.50 − 01	2.08 − 01	3.99 − 01	5.77 − 01	6.74 − 01	1.50 + 00	1.89 + 00	2.47 + 00	
2.00 − 01	1.48 − 01	2.28 − 01	3.07 − 01	3.49 − 01	7.38 − 01	9.45 − 01	1.23 + 00	
3.00 − 01	1.08 − 01	1.31 − 01	1.55 − 01	1.68 − 01	3.02 − 01	3.83 − 01	4.85 − 01	
4.00 − 01	9.19 − 02	1.01 − 01	1.10 − 01	1.16 − 01	1.80 − 01	2.20 − 01	2.73 − 01	
5.00 − 01	8.22 − 02	8.59 − 02	9.11 − 02	9.36 − 02	1.29 − 01	1.54 − 01	1.85 − 01	
6.00 − 01	7.52 − 02	7.67 − 02	7.91 − 02	8.07 − 02	1.03 − 01	1.20 − 01	1.40 − 01	
8.00 − 01	6.55 − 02	6.52 − 02	6.55 − 02	6.61 − 02	7.73 − 02	8.56 − 02	9.64 − 02	
1.00 + 00	5.86 − 02	5.77 − 02	5.71 − 02	5.75 − 02	6.39 − 02	6.90 − 02	7.54 − 02	
1.50 + 00	4.79 − 02	4.68 − 02	4.59 − 02	4.60 − 02	4.88 − 02	5.10 − 02	5.39 − 02	
2.00 + 00	4.19 − 02	4.14 − 02	4.08 − 02	4.09 − 02	4.34 − 02	4.50 − 02	4.70 − 02	
3.00 + 00	3.59 − 02	3.66 − 02	3.67 − 02	3.69 − 02	4.01 − 02	4.16 − 02	4.35 − 02	
4.00 + 00	3.32 − 02	3.48 − 02	3.54 − 02	3.59 − 02	3.98 − 02	4.14 − 02	4.34 − 02	
5.00 + 00	3.18 − 02	3.43 − 02	3.53 − 02	3.59 − 02	4.06 − 02	4.24 − 02	4.44 − 02	
6.00 + 00	3.10 − 02	3.43 − 02	3.57 − 02	3.63 − 02	4.16 − 02	4.34 − 02	4.54 − 02	
8.00 + 00	3.06 − 02	3.50 − 02	3.69 − 02	3.78 − 02	4.39 − 02	4.59 − 02	4.79 − 02	
1.00 + 01	3.08 − 02	3.62 − 02	3.85 − 02	3.95 − 02	4.63 − 02	4.84 − 02	5.06 − 02	
1.50 + 01	3.23 − 02	3.93 − 02	4.25 − 02	4.38 − 02	5.24 − 02	5.48 − 02	5.73 − 02	
2.00 + 01	3.39 − 02	4.23 − 02	4.61 − 02	4.76 − 02	5.77 − 02	6.06 − 02	6.36 − 02	
3.00 + 01	3.68 − 02	4.70 − 02	5.17 − 02	5.36 − 02	6.59 − 02	6.96 − 02	7.33 − 02	

XI. Mass Energy-Absorption Coefficients and f-Factors of Selected Materials [5,10]

Photon energy (eV)	Mass energy-absorption coefficient (μ_{en}/ρ) in m^2/kg (multiply by 10 for cm^2/g)								$f = (0.869)\dfrac{(\mu_{en}/\rho)_{medium}}{(\mu_{en}/\rho)_{air}}$ (rad/R)		
	Air	Water (H_2O)	Polystyrene (C_8H_8)	Lucite ($C_5H_8O_2$)	Polyethylene (CH_2)	Bakelite ($C_{43}H_{38}O_7$)	Compact bone	Muscle	Water	Compact bone	Muscle
1.0000+04	4.648-01	4.839-01	1.849-01	2.943-01	1.717-01	2.467-01	1.900+00	0.496+00	0.912	3.54	0.925
1.5000+04	1.304-01	1.340-01	5.014-02	8.081-02	4.662-02	6.741-02	0.589+00	0.136+00	.889	3.97	.916
2.0000+04	5.266-02	5.364-02	2.002-02	3.231-02	1.868-02	2.692-02	0.251+00	0.544-01	.881	4.23	.916
3.0000+04	1.504-02	1.519-02	6.056-03	9.385-03	5.754-03	7.904-03	0.743-01	0.154-01	.869	4.39	.910
4.0000+04	6.706-03	6.800-03	3.190-03	4.498-03	3.128-03	3.898-03	0.305-01	0.677-02	.878	4.14	.919
5.0000+04	4.038-03	4.153-03	2.387-03	3.019-03	2.410-03	2.711-03	0.158-01	0.409-02	.892	3.58	.926
6.0000+04	3.008-03	3.151-03	2.153-03	2.503-03	2.218-03	2.316-03	0.979-02	0.312-02	.905	2.91	.929
8.0000+04	2.394-03	2.582-03	2.152-03	2.292-03	2.258-03	2.191-03	0.520-02	0.255-02	.932	1.91	.930
1.0000+05	2.319-03	2.539-03	2.292-03	2.363-03	2.419.03	2.288-03	0.386-02	0.252-02	.948	1.45	.918
1.5000+05	2.494-03	2.762-03	2.631-03	2.656-03	2.788-03	2.593-03	0.304-02	0.276-02	.962	1.05	.956
2.0000+05	2.672-03	2.967-03	2.856-03	2.872-03	3.029-03	2.808-03	0.302-02	0.297-02	.973	0.979	.983
3.0000+05	2.872-03	3.192-03	3.088-03	3.099-03	3.275-03	3.032-03	0.311-02	0.317-02	.966	.938	.957
4.0000+05	2.949-03	3.279-03	3.174-03	3.185-03	3.367-03	3.117-03	0.316-02	0.325-02	.966	.928	.954
5.0000+05	2.966-03	3.298-03	3.195-03	3.205-03	3.389-03	3.137-03	0.316-02	0.327-02	.966	.925	.957
6.0000+05	2.952-03	3.284-03	3.181-03	3.191-03	3.375-03	3.123-03	0.315-02	0.326-02	.966	.925	.957
8.0000+05	2.882-03	3.205-03	3.106-03	3.115-03	3.295-03	3.049-03	0.306-02	0.318-02	.965	.920	.956
1.0000+06	2.787-03	3.100-03	3.005-03	3.014-03	3.188-03	2.950-03	0.297-02	0.308-02	.965	.922	.956
1.5000+06	2.545-03	2.831-03	2.744-03	2.752-03	2.911-03	2.693-03	0.270-02	0.281-02	.964	.920	.958
2.0000+06	2.342-03	2.604-03	2.522-03	2.530-03	2.675-03	2.476-03	0.248-02	0.257-02	.968	.921	.954
3.0000+06	2.055-03	2.279-03	2.196-03	2.208-03	2.325-03	2.160-03	0.219-02	0.225-02	.962	.928	.954
4.0000+06	1.868-03	2.064-03	1.978-03	1.993-03	2.089-03	1.950-03	0.199-02	0.203-02	.958	.930	.948
5.0000+06	1.739-03	1.914-03	1.822-03	1.842-03	1.919-03	1.801-03	0.186-02	0.188-02	.954	.934	.944
6.0000+06	1.646-03	1.805-03	1.707-03	1.730-03	1.793-03	1.691-03	0.178-02	0.178-02	.960	.940	.949
8.0000+06	1.522-03	1.658-03	1.548-03	1.578-03	1.618-03	1.541-03	0.165-02	0.163-02	.958	.950	.944
1.0000+07	1.445-03	1.565-03	1.445-03	1.480-03	1.503-03	1.445-03	0.159-02	0.154-02	.935	.960	.929
1.5000+07	1.347-03	1.440-03	1.302-03	1.346-03	1.341-03	1.313-03					
2.0000+07	1.306-03	1.384-03	1.233-03	1.284-03	1.206-03	1.251-03					

XII. Elemental Composition, Atomic Number, and Atomic Mass of Significant Components of Selected Human Tissue Organs (Water Is Included for Reference Purposes) [7,11]

			Organ mass (g)								
Element	Atomic Number	Atomic Mass	Adipose 15055 g	Blood 5394 g	Brain 1400 g	Heart 330 g	Kidney 310 g	Liver 1800 g	Muscle 28,000 g	Pancreas 100 g	Water 1 g
Calcium	20	40.08	3.4–01	3.1–01	1.2–01	1.2–02	2.9–02	9.0–02	8.7–01	9.1–03	
Carbon	6	12.01	9.6+03	5.4+02	1.7+02	5.4+01	4.0+01	2.6+02	3.0+03	1.3+01	
Chlorine	17	35.453	1.8+01	1.5+01	3.2+00	5.4–01	7.4–01	3.6+00	2.2+01	1.6–01	
Hydrogen	1	1.00797	1.8+03	5.5+02	1.5+02	3.4+01	3.2+01	1.8+02	2.8+03	9.7+00	0.111901
Iron	26	55.847	3.6–01	2.5+00	7.4–02	1.5–02	2.3–02	3.2–01	1.1+00	3.9–03	
Magnesium	12	24.305	3.0–01	2.1–01	2.1–01	5.4–02	4.0–02	3.1–01	5.3+00	1.6–02	
Nitrogen	7	14.0067	1.2+02	1.6+02	1.8+01	8.8+00	8.5+00	5.1+01	7.7+02	2.1+00	
Oxygen	8	15.9994	3.5+03	4.1+03	1.0+03	2.3+02	2.3+02	1.2+03	2.1+04	6.7+01	0.888099
Phosphorus	15	30.9738	2.2+00	1.9+00	4.8+00	4.8–01	5.0–01	4.7+00	5.0+01	2.3–01	
Potassium	19	39.102	4.8+00	8.8+00	4.2+00	7.2–01	5.9–01	4.5+00	8.4+01	2.3–01	
Sodium	11	22.9899	7.6+00	1.0+01	2.5+00	4.0+00	6.2–01	1.8+00	2.1+01	1.4–01	
Sulfur	16	32.064	1.1+00	5.5+00	2.4+00	5.4–01	0.0+00	5.2+00	6.7+01		
Zinc	30	65.37	2.7–02	3.4–02	1.7–02	8.4–03	1.5–02	8.5–02	1.5+00	2.5–03	

XIII. Selected Rules of Thumb [12]

The following rules of thumb are only approximate, and should be treated as such!

Alpha Particles

Alpha particles of at least 7.5 MeV are required to penetrate the epidermis, the protective layer of skin, 0.07 mm thick.

Electrons

Electrons of at least 70 keV are required to penetrate the epidermis, the protective layer of skin, 0.07 mm thick.

The range (R) of electrons in g/cm^2 is approximately equal to the maximum energy (E) in MeV divided by 2 (i.e., $R \cong E/2$).

The range of electrons in air is about 3.65 m per MeV; for example, a 3 MeV electron has a range of about 11 m in air.

A chamber wall thickness of 30 mg/cm^2 will transmit 0.7 of the initial fluence of 1 MeV electrons and 0.2 of 0.4-MeV electrons.

When electrons of 1 to 2 MeV pass through light materials such as water, aluminum, or glass, less than 1% of their energy is dissipated as bremsstrahlung.

The bremsstrahlung from 1 Ci of ^{32}P aqueous solution in a glass bottle is about 1 mR/h at 1 meter.

When electrons from a 1 Ci source of ^{90}Sr–^{90}Y are absorbed, the bremsstrahlung hazard is approximately equal to that presented by the gamma radiation from 12 mg of radium. The average energy of the bremsstrahlung is about 300 keV.

Gamma Rays

The air-scattered radiation (sky-shine) from a 100-Ci ^{60}Co source placed 1 ft behind a 4-ft-high shield is about 100 mrad/h at 6 ft from the outside of the shield.

Within ±20% for point source gamma emitters with energies between 0.07 and 4 MeV, the exposure rate (R/h) at 1 ft is $6 \cdot C \cdot E \cdot n$ where C is the activity in curies, E the energy in MeV, and n is the number of gammas per disintegration.

Neutrons

An approximate HVL for 1-MeV neutrons is 3.2 cm of paraffin; that for 5-MeV neutrons is 6.93 cm.

Miscellaneous

The activity of any radionuclide is reduced to less than 1% after 7 half-lives (i.e., $2^{-7} = 0.8\%$).

For material with a half-life greater than 6 days, the change in activity in 24 hours will be less than 10%.

There is 0.64 mm^3 of radon gas in transient equilibrium with 1 Ci of radium.

1 year $\cong \pi \times 10^7$ s.

10 HVL attenuates approximately by 10^{-3}.

XIV. Some Characteristics of the Standard Man [13]

A. Mass of organs of the standard adult human body

Tissue or organ	Mass[a] (g)		% of total body	
Adipose tissue	15000		21	
Subcutaneous		7500		11
Other separable		5000		7.1
Interstitial	1000		1.4	
Yellow marrow (included with skeleton)	1500		2.1	
Adrenals (2)		14		0.02
Aorta		100		0.14
Contents (blood)		190 (180 ml)		0.27
Blood-total	5500 g (5200 ml)		7.8	
Plasma	3100 g (3000 ml)		4.4	
Erythrocytes	2400 g (2200 ml)		3.4	
Blood vessels (not including aorta and pulmonary)		200		0.29
Contents (blood)		3000 (2900 ml)		4.3
Cartilage (included with skeleton)	1100		1.6	
Connective tissue	3400		4.8	
Tendons and fascia	1400		2.0	
Periarticular tissue	1500		2.1	
Other connective tissue	500		0.7	
Separable connective tissue		1600		2.3
Central Nervous System		1430		2.04
Brain	1400		2.0	
Spinal cord	30		0.04	
Contents-cerebrospinal fluid		120 (120 ml)		0.17
Eyes		15		0.02
Lenses (2)	0.4			
Gall bladder		10		0.01
Contents (bile)		62 (60 ml)		0.09
GI tract		1200		1.7
Esophagus	40		0.06	
Stomach	150		0.21	
Intestine	1000		1.4	
Small	640		0.91	
Upper large	210		0.30	
Lower large	160		0.23	
Contents of GI tract (food plus digestive fluids)		1005		1.4
Hair		20		0.03
Heart		330		0.47
Contents (blood)		500 (470 ml)		0.71
Kidneys		310		0.44
Larynx		28		0.04
Liver		1800		2.6

Tissue or organ	Mass[a] (g)		% of total body	
Lungs		1000		1.4
Parenchyma (includes bronchial tree, capillary blood, and associated lymph nodes)	570		0.81	
Pulmonary blood	430 (400 ml)		0.61	
Lymphocytes	1500		2.1	
Lymphatic tissue	700		1.0	
Lymph nodes (dissectible)		250		0.36
Miscellaneous (by difference)		2953.1		4.2
Soft tissue (nasopharynx, etc.)	300		0.43	
Fluids (synovial, pleural, etc.)	350		0.50	
Muscle (skeletal)		28,000		40.0
Nails		3		
Pancreas		100		0.14
Parathyroids		0.12		
Pineal		0.18		
Pituitary		0.6		
Prostate		16		0.023
Salivary glands		85		0.12
Skeleton		10,000		14
Bone	5000		7.2	
Cortical	4000		5.7	
Trabecular	1000		1.4	
Red Marrow	1500		2.1	
Yellow Marrow	1500		2.1	
Cartilage	1100		1.6	
Periarticular tissue (skeletal)	900		1.3	
Skin		2600		3.7
Epidermis	100		0.14	
Dermis	2500		3.6	
Hypodermis	7500		11	
Spleen		180		0.26
Teeth		46		0.066
Testes		35		0.05
Thymus		20		0.029
Thyroid		20		0.029
Tongue		70		0.10
Tonsils		4		0.006
Trachea		10		0.014
Ureters		16		0.023
Urethra		10		0.014
Urinary bladder		45		0.064
Contents (urine)		102 (100 ml)		0.15
Total body		70,000		100

[a] Values for organs and tissues listed in the right hand column under "Mass" make up the totality of Reference Man (70,000 g).

B. Chemical composition, adult human body

Element	Amount (g)	Percent of total body weight
Oxygen	43,000	61
Carbon	16,000	23
Hydrogen	7000	10
Nitrogen	1800	2.6
Calcium	1000	1.4
Phosphorus	780	1.1
Sulfur	140	0.20
Potassium	140	0.20
Sodium	100	0.14
Chlorine	95	0.12
Magnesium	19	0.027
Silicon	18	0.026
Iron	4.2	0.006
Fluorine	2.6	0.0037
Zinc	2.3	0.0033
Rubidium	0.32	0.00046
Strontium	0.32	0.00046
Bromine	0.20	0.00029
Lead	0.12	0.00017
Copper	0.072	0.00010
Aluminum	0.061	0.00009
Cadmium	0.050	0.00007
Boron	<0.048	0.00007
Barium	0.022	0.00003
Tin	<0.017	0.00002
Manganese	0.012	0.00002
Iodine	0.013	0.00002
Nickel	0.010	0.00001
Gold	<0.010	0.00001
Molybdenum	<0.0093	0.00001
Chromium	<0.0018	0.000003
Cesium	0.0015	0.000002
Cobalt	0.0015	0.000002
Uranium	0.00009	0.0000001
Beryllium	0.000036	
Radium	3.1×10^{-11}	

References to Chapter One

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Notes

Notes

CHAPTER TWO: NUCLEAR MEDICINE

I. Physical Characteristics of Clinically Used Radionuclides [1-3]

Radio-nuclide	Principal means of production	Half-life	Major radiations-energies (MeV)-abundance (%) Beta	Gamma	Γ, specific γ-ray constant (R·cm²/h·mCi)	Half-value layer in Pb (cm)
^{3}H	^{6}Li(n,α)^{3}H	12.3 y	0.018(100)			
^{11}C	^{11}B(p,n)^{11}C	20.3 m	β^+ 0.97(100)	0.511(200)	5.91	0.4
^{14}C	^{14}N(n,p)^{14}C	5.73×10^3 y	0.16(100)			
^{13}N	^{13}C(p,n)^{13}N	10.0 m	β^+ 1.20(100)	0.511(200)	5.91	0.4
^{15}O	^{14}N(d,n)^{15}O	2.07 m	β^+ 1.74(100)	0.511(200)	5.91	0.4
^{18}F	^{19}F(p,pn)^{18}F	1.8 h	β^+ 0.65(97)	0.511(194)	5.73	0.4
^{24}Na	^{23}Na(n,γ)^{24}Na	15.0 h	1.4(100)	1.369(100) 2.754(100)	18.40	1.5
^{32}P	^{31}S(n,p)^{32}P ^{31}P(n,γ)^{32}P	14.3 d	1.7(100)			
^{35}S	^{35}Cl(n,p)^{35}S ^{34}S(n,γ)^{35}S	88.0 d	0.17(100)			
^{42}K	^{41}K(n,γ)^{42}K	12.4 h	2.00(18) 3.52(82)	1.524(18)	1.35	
^{43}K	^{40}Ar(α,p)^{43}K	22.4 h	0.83(87)	0.371(85) 0.338(07) 0.394(11) 0.590(13) 0.619(81)	5.60	
^{45}Ca	^{44}Ca(n,γ)^{45}Ca	165 d	0.25(100)			
^{47}Ca	^{46}Ca(n,γ)^{47}Ca	4.56 d	0.67(82) 1.98(18)	0.490(5) 0.815(5) 1.308(74)	5.70	
^{51}Cr	^{50}Cr(n,γ)^{51}Cr	27.8 d	0.3e$^-$ (trace)	0.320(9)	0.164	0.2
^{52}Fe	^{50}Cr(α,2n)^{52}Fe	8.3 h	β^+ 0.80(56)	0.165(100) 0.511(112)	17.20	1.2
^{55}Fe	^{54}Fe(n,γ)^{55}Fe	2.7 y		0.006(13) Mn x-rays		
^{59}Fe	^{58}Fe(n,γ)^{59}Fe	45 d	0.48(99)	1.095(56) 1.292(44)	6.20	1.1
^{57}Co	^{60}Ni(p,α)^{57}Co	267 d		0.014(9) 0.122(87) 0.136(10)	0.93	0.03
^{58}Co	^{55}Mn(α,n)^{58}Co	71.3 d	β^+ 0.47(15)	0.511(30) 0.811(99)	5.50	
^{60}Co	^{59}Co(n,γ)^{60}Co	5.26 y	0.31(99$^+$)	1.173(100) 1.332(100)	13.20	1.2

Radio-nuclide	Principal means of production	Half-life	Major radiations-energies (MeV)-abundance (%) Beta	Gamma	Γ, specific γ-ray constant (R·cm²/h·mCi)	Half-value layer in Pb (cm)
^{64}Cu	$^{63}Cu(n,\gamma)^{64}Cu$	12.9 h	0.57(39) β^+ 0.64(19)	0.511(38)	1.16	0.4
^{65}Zn	$^{64}Zn(n,\gamma)^{65}Zn$	245 d	1.1e$^-$ (trace) β^+ 0.33(2)	1.150(49)	2.70	1.0
^{67}Ga	$^{67}Zn(p,n)^{67}Ga$	78 h	0.09e$^-$ (15)	0.093(40) 0.185(24) 0.296(22) 0.388(7)	~1.1	
^{68}Ga	$^{68}Zn(p,n)^{68}Ga$	1.13 h	β^+ 1.90(87)	0.511(176)	5.37	0.4
^{75}Se	$^{74}Se(n,\gamma)^{75}Se$	120 d	e$^-$ 0.08–0.25	0.121(16) 0.136(57) 0.265(60) 0.280(25) 0.401(13)	2.00	0.2
^{85m}Kr	$^{84}Kr(n,\gamma)^{85m}Kr$	4.4 h	0.82(77)	0.150(74) 0.305(16)	1.29	
^{85}Sr	$^{84}Sr(n,\gamma)^{85}Sr$	64 d	0.5(1)	0.514(100)	3.00	0.4
^{87m}Sr	^{87}Y daughter	2.8 h	0.4e$^-$ (22)	0.388(80)	1.74	
^{90}Sr	Fission	28 y	0.55(100) ^{90}Y–2.30(100)			
^{86}Rb	$^{85}Rb(n,\gamma)^{86}Rb$	18.7 d	0.70(9) 1.78(9)	1.078(9)	0.49	1.0
^{99}Mo	$^{98}Mo(n,\gamma)^{99}Mo$	66.7 h	1.23(82) 0.45(17)	0.181(7) 0.740(14) 0.778(5)	~1.80	
^{99m}Tc	^{99}Mo daughter	6.04 h	0.12e$^-$ (trace)	0.140(90)	0.70	0.03
^{111}In	$^{111}Cd(p,n)^{111}In$	2.8 d	0.15–0.24e$^-$(15)	0.173(89) 0.247(94)		
^{113m}In	Daughter ^{113}Sn	1.67 h		0.393(65)	0.32(x) 1.57(γ) ~1.7	0.03
^{123}I	$^{123}Te(p,n)^{123}I$	13.0 h	0.13e$^-$ (trace)	0.159(97)	0.97(x) 0.66(γ)	0.04
^{125}I	$^{124}Xe(n,\gamma) \rightarrow$ $^{125}Xe \rightarrow {}^{125}I$	60.2 d	0.03e$^-$ (90)	0.036(7) 0.027 x-rays (90)	~0.70	
^{129}I	Fission	1.7×10^7 y	0.150(100)	0.04(9) Xe x-rays		
^{131}I	Fission	8.05 d	0.61(90)	0.284(5) 0.365(83) 0.637(7)	2.23	0.3

Radio-nuclide	Principal means of production	Half-life	Major radiations-energies (MeV)-abundance (%) Beta	Gamma	Γ, specific γ-ray constant (R·cm²/h·mCi)	Half-value layer in Pb (cm)
^{127}Xe	$^{127}I(p,n)^{127}Xe$	36.4 d		0.172(22) 0.203(65) 0.375(20)		
^{133}Xe	Fission	5.3 d	0.35(100)	0.08(35) Cs x-rays	0.10	
^{129}Cs	$^{127}I(\alpha,2n)^{129}Cs$	32.1 h		0.375(48) 0.416(25) 0.550(5)		
^{137}Cs	Fission	30 y	0.51(95) 1.18(7)	0.662(84)	3.32	0.6
^{198}Au	$^{197}Au(n,\gamma)^{198}Au$	2.7 d	0.97(99)	0.412(96)	2.34	0.3
^{197}Hg	$^{196}Hg(n,\gamma)^{197}Hg$	2.7 d		0.077(19)	~0.40	
^{203}Hg	$^{202}Hg(n,\gamma)^{203}Hg$	47 d	0.214(100)	0.279(82)	1.33	
^{169}Yb	$^{168}Yb(n,\gamma)^{169}Yb$	31.8 d		0.063(45) 0.177(22) 0.110(18) 0.197(35) 0.131(11) 0.308(10)		
^{201}Tl	Daughter ^{201}Pb	73 h		0.167(8) Hg x-rays	0.08	

II. Radiopharmaceutical Dosimetry

A. Formula

The average absorbed doses to total body and to specific organs for administered radionuclides can be calculated from [4,5]:

$$D(r_k \leftarrow r_h) = \tilde{A}_h \left[\frac{\Sigma_n \Delta_n \cdot \phi_n(r_k \leftarrow r_h) + \Sigma_p \Delta_p \cdot \phi_p(r_k \leftarrow r_h)}{m_k} \right]$$

$$= \tilde{A}_h \, [\Sigma_n \Delta_n \cdot \Phi_n(r_k \leftarrow r_h) + \Sigma_p \Delta_p \cdot \Phi_p(r_k \leftarrow r_h)]$$

$$= \tilde{A}_h \cdot S$$

where

$D(r_k \leftarrow r_h)$ = average dose (rad) to target volume r_k from radioactivity located in source volume r_h

$\tilde{A}_h$ = cumulated activity in source volume r_h (μCi·h)

m_k = mass of the target volume r_k (g)

n = nonpenetrating radiation

p = penetrating radiation

Δ = equilibrium dose constant (g·rad/μCi·h)

$\phi(r_k \leftarrow r_h)$ = the fraction of energy emitted by activity in source volume r_h which is absorbed in target volume r_k

$\Phi(r_k \leftarrow r_h)$ = specific absorbed fraction (g^{-1})

S = mean dose per unit cumulated activity (rad/μCi·h)

B. Schedule for calculation of pediatric-administered activities (based on body weight) [6]

Mass (kg)	Fraction of adult activity	Mass (kg)	Fraction of adult activity
2	0.09	25	0.50
3	0.12	30	0.57
4	0.14	35	0.63
5	0.17	40	0.69
6	0.19	45	0.74
7	0.21	50	0.80
8	0.23	55	0.85
9	0.25	60	0.90
10	0.27	65	0.95
15	0.36	70	1.00
20	0.43		

C. Whole body dose from selected radiopharmaceuticals [7-9]

Radio-nuclide	Radio-pharmaceutical	Whole body doses (mrad/μCi administered) Newborn	1	5	10	15	Adult
				years of age			
^{51}Cr	Red Blood Cells	7.00	2.50	1.50	1.00	0.60	0.50
^{57}Co	Vitamin B12						10.00
^{67}Ga	Citrate	1.40	0.57	0.38	0.28	0.20	0.16
^{75}Se	Selenomethionine						8.00
^{99m}Tc	DTPA	0.170	0.062	0.043	0.029	0.021	0.016
	HSA	0.180	0.062	0.040	0.026	0.017	0.015
	Iron Complex	0.086	0.033	0.022	0.015	0.010	0.009
	MAA	0.177	0.064	0.042	0.028	0.019	0.015
	Pertechnetate	0.151	0.055	0.037	0.024	0.016	0.013
	Polyphosphate	0.131	0.049	0.034	0.021	0.013	0.011
	EHDP	0.173	0.065	0.045	0.028	0.017	0.015
	Red Blood Cells	0.200	0.070	0.040	0.030	0.020	0.016
	Sulfur Colloid	0.140	0.056	0.038	0.027	0.020	0.016
^{111}In	DTPA	1.80	0.52	0.32	0.20	0.12	0.10
^{113m}In	Colloid	0.077	0.031	0.023	0.015	0.011	0.009
	DTPA	0.130	0.039	0.024	0.015	0.0094	0.0074
	Iron Hydroxide	0.250	0.080	0.052	0.032	0.021	0.017
^{123}I	Iodide	0.35	0.13	0.08	0.05	0.045	0.030
^{125}I	Iodide	9.40	1.60	1.00	0.67	0.44	0.34
	Fibrinogen						0.20
^{131}I	HSA	24.00	7.60	4.80	3.00	1.90	1.60
	MAA	5.20	1.90	1.00	0.65	0.42	0.35
	Iodide	10.00	2.00	1.30	0.81	0.52	0.45
	Rose Bengal	5.10	1.80	0.89	0.53	0.36	0.29
^{129}Cs	Chloride	3.00	1.00	0.70	0.45	0.30	0.25
^{201}Tl							0.24

D. Critical organ doses from selected radiopharmaceuticals [7-9]

Radio-nuclide	Radio-pharmaceutical	Critical organ	Critical organ dose (mrad/μCi administered) Newborn	1	5	10	15	Adult
				years of age				
^{18}F	Fluoride	bone	2.40	0.65	0.45	0.29	0.19	0.18
^{51}Cr	Red Blood Cells (heat treated)	spleen	336.0	90.1	56.2	30.5	24.1	22.5
^{57}Co	Vitamin B12	liver	1088.0	433.0	260.0	183.4	144.0	114.0
^{59}Fe	Citrate, Chloride	spleen						130.0
^{67}Ga	Citrate	spleen	8.02	2.60	1.64	1.00	0.71	0.60
^{75}Se	Selenomethionine	liver	187.0	83.2	52.9	38.5	30.8	25.0
^{99m}Tc	DTPA	bladder[a]	5.00	1.70	1.10	0.80	0.56	0.45
		kidney	0.39	0.15	0.10	0.07	0.05	0.04
	HSA	blood	0.81	0.24	0.15	0.09	0.06	0.05
	Iron Complex	renal cortex	5.20	1.80	1.20	0.77	0.61	0.55
	MAA	lung	3.09	1.00	0.59	0.35	0.26	0.20
	Pertechnetate	LLI[b]	1.91	0.67	0.46	0.33	0.23	0.20
	Polyphosphate	bone	1.10	0.32	0.23	0.15	0.10	0.08
	Red Blood Cells (heat treated)	spleen	26.0	9.23	5.21	3.07	2.70	2.60
	Sulfur Colloid	liver	2.90	1.34	0.92	0.56	0.40	0.33
^{111}In	Colloid	liver	20.3	9.0	5.2	3.3	2.4	2.0
	DTPA	brain (max)	47.0	20.0	17.0	16.0	15.0	14.0
		bladder	24.6	7.5	4.4	2.8	1.9	1.5
	Iron Hydroxide	lung	14.7	4.5	2.5	1.5	1.1	0.8
^{113m}In	Iron Hydroxide	lung	9.52	2.89	1.62	0.95	0.72	0.50
	Colloid	liver	4.76	2.11	1.23	0.78	0.56	0.47
	DTPA	bladder[a]	7.15	2.16	1.28	0.82	0.55	0.43
^{123}I	Hippuran	kidney	0.69	0.23	0.18	0.13	0.10	0.07
	Rose Bengal	liver	1.89	0.75	0.46	0.32	0.24	0.20
^{131}I	Hippuran	kidney	9.52	4.44	3.08	2.22	1.20	1.00
	HSA	blood	309.5	92.2	55.4	32.7	20.8	16.0
	MAA	lung	73.8	22.2	13.1	7.80	5.60	4.00
	Rose Bengal	liver	8.10	3.00	1.77	1.22	0.84	0.67
^{127}Xe	Gas	lung						0.0047[c]
^{133}Xe	Gas	lung						0.0098[c]
^{169}Yb	DTPA (i.v.)	kidney	106.0	33.8	23.3	17.4	14.9	8.5
	DTPA (i.v.)	brain (max)	10.8	4.6	3.9	3.7	3.4	3.2
	DTPA (intrathecal)	brain	236.0	93.0	76.5	73.5	72.0	70.0
^{201}Tl		kidneys						0.39
		heart						0.17

[a] Assumes 6-hour bladder residence time.
[b] Perchlorate blocking dose (i.v. administration).
[c] Consists of an initial 30-second breath-hold after normal inspiration, followed by a 4-minute rebreathing period and subsequent washout.

E. Thyroid dose (rad/μCi administered) [7]

Radio-pharmaceutical	Newborn (1.5)[a]	1 y (2.2)	5 y (4.7)	10 y (8.0)	15 y (11.2)	Adult (16.0)
^{123}I (Iodide)[b]	0.119	0.081	0.038	0.022	0.016	0.011
^{125}I (Iodide)[b]	8.23	5.63	2.62	1.55	1.11	0.77
^{131}I (Iodide)[b]	11.80	8.09	3.78	2.22	1.55	1.11
^{99m}Tc (Pertechnetate)[c]	0.0034	0.0013	0.0008	0.0005	0.0004	0.0002

[a] Numbers in parentheses indicated thyroid gland weight in grams.
[b] Assumed uptake–20 percent.
[c] Assumed uptake–5 percent.

F. Gonadal doses from selected radiopharmaceuticals [10]

Scintigraphic study	Radiopharmaceutical	Gonads	Gonadal dose (mrad/μCi administered) Newborn	1	5	10	15	Adult
					years of age			
Bone	^{99m}Tc (phosphate)	M	0.289	0.224	0.207	0.187	0.041	0.034
		F	0.561	0.193	0.115	0.083	0.055	0.046
Brain	^{99m}Tc (pertechnetate)	M	0.102	0.079	0.073	0.066	0.014	0.012
		F	0.219	0.076	0.045	0.032	0.022	0.018
Cardiac	^{99m}Tc (albumin)	M	0.340	0.264	0.244	0.220	0.048	0.040
		F	0.658	0.227	0.135	0.097	0.065	0.054
Kidney	^{99m}Tc (DTPA)	M	0.170	0.132	0.122	0.110	0.024	0.020
		F	0.329	0.113	0.068	0.049	0.032	0.027
Liver	^{99m}Tc (sulfur colloid)	M	0.161	0.125	0.116	0.104	0.023	0.019
		F	0.280	0.097	0.058	0.041	0.028	0.023
Lung	^{99m}Tc (MAA)	M	0.060	0.046	0.043	0.038	0.008	0.007
		F	0.110	0.038	0.022	0.016	0.010	0.009
Thyroid	^{123}I (sodium iodide)	M	0.085	0.066	0.061	0.055	0.012	0.010
		F	0.244	0.084	0.050	0.036	0.024	0.020

G. Dose estimates to embryo [11]

Radiopharmaceutical administered	Embryo dose (rad/mCi)
^{99m}Tc-human serum albumin	0.018[a]
^{99m}Tc-lung	0.035[a]
^{99m}Tc-polyphosphate	0.036[a]
^{99m}Tc-sodium pertechnetate	0.037
^{99m}Tc-stannous glucoheptonate	0.040[a]
^{99m}Tc-sulfur colloid	0.032[a]
^{123}I-sodium iodide (15% uptake)	0.032
^{131}I-sodium iodide (15% uptake)	0.100
^{123}I-rose bengal	0.130
^{131}I-rose bengal	0.680

[a] These values were calculated using cumulated activity ($\tilde{A}$) values from company product data and absorbed dose per cumulated activity (S) values from reference [11].

H. Thyroidal radioiodine exposure of fetus [12]

Gestation period	Fetal/maternal ratio (thyroid gland)	Thyroid dose (fetus) rad/(μCi)[a]
10–12 weeks		.001 (precursors)
12–13 weeks	1.2	0.7
2nd trimester	1.8	6.0
3rd trimester	7.5	
birth imminent		8.0

[a] rad/μCi of ^{131}I ingested by mother.

III. Radiation Safety

A. License-exempt levels of activity [13]

Radionuclide	Microcuries	Radionuclide	Microcuries
Calcium-45	10	Krypton-85	100
Calcium-47	10	Mercury-197	100
Carbon-14	100	Mercury-203	10
Cesium-137	10	Molybdenum-99	100
Chromium-51	1,000	Phosphorus-32	10
Cobalt-58	10	Potassium-42	10
Cobalt-60	1	Rubidium-86	10
Copper-64	100	Selenium-75	10
Fluorine-18	1,000	Sodium-24	10
Gold-198	100	Strontium-85	10
Hydrogen-3	1,000	Strontium-90	0.1
Indium-113m	100	Sulfur-35	100
Iodine-125	1	Technetium-99m	100
Iodine-129	0.1	Thallium-201	100
Iodine-131	1	Xenon-133	100
Iron-55	100	Zinc-65	10
Iron-59	10		

Any alpha emitting radionuclide not listed above or mixtures of alpha emitters of unknown composition, 0.01 μCi.

Any radionuclide other than alpha emitting radionuclides not listed above or mixtures of beta emitters of unknown composition, 0.1 μCi.

B. Levels to be used as a guide in the establishment of contamination zones [14]

Type of radiation	Airborne contamination (μCi/cm^3 in air)	Direct reading surface contamination	Transferable surface contamination (dpm/100 cm^2)
α	2×10^{-12}	300 dpm/100 cm^2	30
β,γ	3×10^{-10}	0.25 mrad/h	1,000

C. Maximum permissible contamination guide for skin surfaces [14]

	Direct survey		Transferable (smear)
Surface	α (dpm/100 cm^2)	β,γ (mrad/h)	α,β,γ
General body	150	<0.06	None detectable
Hands	150	<0.3	

D. Maximum permissible contamination on clothing [14]

Item	Direct survey α (dpm/100 cm²)	Direct survey β,γ (mrad/h)	Transferable (smear) α (dpm/100 cm²)	Transferable (smear) β,γ (dpm/100 cm²)
Shoes, contamination zone:				
Inside	300	1.0	30	1,000
Outside	300	2.5	30	1,000
Shoes, personal:				
Inside	300	0.3	30	1,000
Outside	300	.6	30	1,000
Clothing, contamination zone	150	.75		
Clothing, other company issued, and personal	150	.25		

E. Permissible contamination for items given radiation clearance [14]

Direct survey α (dpm/100 cm²)	Direct survey β,γ (mrad/h)	Transferable (smear) α (dpm/100 cm²)	Transferable (smear) β,γ (dpm/100 cm²)
<300	<0.05	<30	<200

F. Permissible concentrations and pertinent radiologic data of selected radionuclides [13,15]

Isotope	MPBB (μCi)	Critical organ[a]	MPC (air) workers (μCi/cm^3)	MPC (air) public (μCi/cm^3)	MPC (water) workers (μCi/cm^3)	MPC (water) public (μCi/cm^3)
Ca-47	5	Bone	2×10^{-7}	6×10^{-9}	1×10^{-3}	3×10^{-5}
C-14	300	Fat	4×10^{-6}	1×10^{-7}	2×10^{-2}	8×10^{-4}
Cs-137	30	T.B.	1×10^{-8}	5×10^{-10}	4×10^{-4}	2×10^{-5}
Cr-51	800	T.B.	2×10^{-6}	8×10^{-8}	5×10^{-2}	2×10^{-3}
Co-57	200	T.B.	2×10^{-7}	6×10^{-9}	1×10^{-2}	4×10^{-4}
Co-58	30	T.B.	5×10^{-8}	2×10^{-9}	3×10^{-3}	9×10^{-5}
Co-60	10	T.B.	9×10^{-9}	3×10^{-10}	1×10^{-3}	3×10^{-5}
Cu-64	10	Spl.	1×10^{-6}	4×10^{-8}	6×10^{-3}	2×10^{-4}
F-18	20	T.B.	3×10^{-6}	9×10^{-8}	1×10^{-2}	5×10^{-4}
Au-198	20	Kid.	2×10^{-7}	8×10^{-9}	1×10^{-3}	5×10^{-5}
H-3	1000	B.T.	5×10^{-6}	2×10^{-7}	1×10^{-1}	3×10^{-3}
In-113m	30	Kid.	7×10^{-6}	2×10^{-7}	4×10^{-2}	1×10^{-3}
I-125			5×10^{-9}	8×10^{-11}	4×10^{-5}	2×10^{-7}
I-129	3	Thy.	2×10^{-9}	2×10^{-11}	1×10^{-5}	6×10^{-8}
I-131	0.7	Thy.	9×10^{-9}	1×10^{-10}	6×10^{-5}	3×10^{-7}
Fe-55	1000	Spl.	9×10^{-7}	3×10^{-8}	2×10^{-2}	8×10^{-4}
Fe-59	20	Spl.	5×10^{-9}	2×10^{-9}	2×10^{-3}	5×10^{-5}
Kr-85			1×10^{-5}	3×10^{-7}		
Hg-197	20	Kid.	1×10^{-6}	4×10^{-8}	9×10^{-3}	3×10^{-4}
Hg-203	4	Kid.	7×10^{-8}	2×10^{-9}	5×10^{-4}	2×10^{-5}
Mo-99	8	Kid.	2×10^{-7}	7×10^{-9}	1×10^{-3}	4×10^{-5}
P-32	6	Bone	7×10^{-8}	2×10^{-9}	5×10^{-4}	2×10^{-5}
K-42	10	T.B.	1×10^{-7}	4×10^{-9}	6×10^{-4}	2×10^{-5}
Rb-86	30	T.B.	7×10^{-8}	2×10^{-9}	7×10^{-4}	2×10^{-5}
Se-75	90	Kid.	1×10^{-7}	4×10^{-9}	8×10^{-3}	3×10^{-4}
Na-24	7	T.B.	1×10^{-7}	5×10^{-9}	8×10^{-4}	3×10^{-5}
Sr-85	60	T.B.	1×10^{-7}	4×10^{-9}	3×10^{-3}	1×10^{-4}
Sr-90	2	Bone	1×10^{-9}	3×10^{-11}	1×10^{-5}	3×10^{-7}
S-35	90	Test.	3×10^{-7}	9×10^{-9}	2×10^{-3}	6×10^{-5}
Tc-99m	200	T.B.	1×10^{-5}	5×10^{-7}	8×10^{-2}	3×10^{-3}
Tl-201	40	Kid.	9×10^{-7}	3×10^{-8}	5×10^{-3}	2×10^{-4}
Xe-133			1×10^{-5}	3×10^{-7}		
Zn-65	60	T.B.	6×10^{-8}	2×10^{-9}	3×10^{-3}	1×10^{-4}

[a] T.B.—total body; Spl—spleen; B.T.—body tissue; Kid.—kidney; Thy.—Thyroid; Test.—testes.
MPC—maximum permissible concentration.
MPBB—maximum permissible body burden.

G. Decontamination of personnel and equipment [14]

(Where possible, the preferred decontaminating agent is listed first)

Contaminated area	Decontaminating agent	Remarks	Maximum suggested levels of contamination
			ALPHA
Skin and hands	Mild soap and water or detergent and water.	Wash 2–3 min and monitor. Do not wash over 3–4 times.	150 d/min/100 cm^2
	If necessary, follow by soft brush, heavy lather, and tepid water.	Use light pressure with heavy lather. Wash for 2 min, 3 times. Rinse and monitor. Use care not to scratch or erode skin.	This is approximately one-half the inhalation level in terms of total dis/min/day. This assumes not more than one-fifth of this material will be inhaled. Additional possible exposure by ingestion is also considered.
	Lava soap and water.	Apply lanolin or hand cream to prevent chapping.	
	OTHER PROCEDURES		BETA-GAMMA
	A mixture of 50 percent Tide and 50 percent corn meal.	Make into a paste. Use with additional water with a mild scrubbing action. Use care not to scratch or erode the skin.	Average less than 0.3 mR/hr for each hand surface or 100 cm^2 of skin surface, using Geiger-Mueller instrument calibrated with Ra^{226}.
	A 5 percent water solution of a mixture of 30 percent Tide, 65 percent Calgon, and 5 percent Carbose (Carboxymethyl Cellulose).	Use with water. Rub for a minute and rinse.	
	A preparation of 8 percent Carbose, 3 percent Tide, 1 percent Versene and 88 percent water homogenized into a cream.	Use without any additional water. Rub for 1 min and wipe off. Follow with lanolin or hand cream.	
	CHEMICAL PROCEDURES	(*As a last resort*)	
	Titanium dioxide paste. Prepare paste by mixing precipitated titanium dioxide (a very thick slurry never permitted to dry) with a small amount of lanolin.	Work the paste into affected area for 2 min. Rinse and wash with soap, brush, and warm water. Monitor.	

Contaminated area	Decontaminating agent	Remarks	Maximum suggested levels of contamination
Skin and hands—Continued	CHEMICAL PROCEDURES—Continued		BETA-GAMMA—Continued
	Mix equal volumes of a saturated solution of potassium permanganate and 0.2 *N* sulfuric acid. Continue with the next step also. (Saturated solution $KMnO_4$ is 6.4 gms per 100 ml of water.)	Pour over wet hands, rubbing the surface and using hand brush for not more than 2 min. (Note: will remove a layer of skin if in contact with the skin for more than 2 min.) Rinse with water.	
	Apply a freshly prepared 5 percent solution of sodium acid sulfite ($NaHSO_3$).	Apply in the same manner as above. Apply for not more than 2 min.	
		The above procedure may be repeated. Apply lanolin or hand cream when completed.	
Wounds (cuts and breaks in the skin).	Running tap water. Report to Medical Officer and RSO as soon as possible.	Wash the wound with large volumes of running water immediately (within 15 sec). Spread the edges of wound to permit flushing action by the water.	Keep wound contamination as low as possible.
Ingestion by swallowing.	Immediately induce vomiting. Drink large quantities of liquids to dilute the activity.	Urine and fecal analysis will be necessary to determine amount of radionuclides in the body.	
			ALPHA
Clothing	Wash—if levels permits	Use standard laundering procedures, 3 percent versene or citric acid may be added to wash water.	150 d/m/100 cm^2
			BETA-GAMMA
		Wash water must be below the MPL for sewer disposal. See NCRP Report 22	No area to average more than 0.1 mR/hr. G-M meter Ra^{226} calibrated.
See rubber and leather under specific materials.	Store	To allow for decay if contamination is short lived.	(If clothing is worn 100 hr/wk, this will give 1/10 of maximum external dose.)
	Disposal	Treat as solid waste if necessary.	
Glassware	Soap or detergent and water.	Monitor wash water and plan disposal of it.	The maximum permissible levels for glassware that is handled with the bare hands is the same as for the hands and skin.
	Chromic acid cleaning solution or concentrated nitric acid.	Monitor wash water and plan disposal of it.	

Contaminated area	Decontaminating agent	Remarks	Maximum suggested levels of contamination
Glassware—Con.	SUGGESTED AGENTS	ELEMENTS REMOVED	BETA-GAMMA—Continued
	Oxalic acid 5 percent (Caution Poison).	*Zr*, *Nb*, *Hf*.	
	Versene (EDTA) 5 percent conc. NH_4OH 3 percent.	Alkaline Earth Metals: *Be*, *Mg*, *Ca*, *Sr*, *Ba*, *Ra*, *P as* PO_4.	
	HCl 10 percent by volume.	Alkali Metals: *Na*, *K*, *Rb*, *Cs*, and strongly absorbed metals like Po.	
	To make, dissolve in order:		
	(1) Versene (EDTA) 5 percent.	Trivalent Metals: *Al*, *Sc*, *Y*, *La Ce*, *Pr*, *Nd*, *Pm*, *Sa*, *Eu*.	
	(2) Conc. NH_4OH, 3 percent by volume.	Rare Earths: *Ac*, *Ga*, *In*, *Ti*, *B*.	
	(3) Glacial acetic acid 5 percent by volume.	Transition Metals: *Cu*, *Zn*, *Fe*, *Co*, *Ni*, *Cd*, *Sn*, *Hg Pb*, *Th*, *U*, *Ag*. (Always consider the radio-activity of the cleaning solution when disposing of it.)	
Laboratory tools	Detergents and water, steam cleaning.	Use mechanical scrubbing action.	The maximum permissible levels for tools that are handled with the bare hands is the same as for the hands and skin.
Metal tools	Dilute nitric acid, 10 percent solution of sodium citrate or ammonium bifluoride.	As a last resort, use HCl on stainless steel.	
	Metal polish, sandblasting, other abrasives.	Such as brass polish on brass. Use caution as these procedures may spread contamination.	
Plastic tools	Ammonium citrates, dilute acids, organic solvents.		
Glass tools	The same as above section on glassware.		
Walls, floors, and benches.	Detergents and water with mechanical action.		
	Vacuum cleaning	The exhaust of the cleaner must be filtered to prevent escape of contamination.	
	Water from high pressure sources. Steam cleaning.	This may spread contamination.	
SPECIFIC MATERIALS			
Rubber	Washing or dilute HNO_3	(Short lived contamination may be covered up to await decay.)	
Glass, plastic	See the above section.		

Contaminated area	Decontaminating agent	Remarks	Maximum suggested levels of eontamination
Leather	Very diffieult to deeontaminate.		
Linoleum	CCl_4, kerosene, ammonium eitrate, dilute mineral aeids.		
Ceramic tile	Mineral acids, ammonium citrate, trisodium phosphate.	Serub hot 10 pereent solution into surface and flush thoroughly with hot water.	
Paint	CCl_4, 10 pereent HCl aeid.	Usually best to remove the paint and repaint.	
Briek and concrete	32 pereent HCl aeid	If this is not suceessful eonerete must be removed.	
Wood	Hot eitrie aeid, remove the wood with a plane or floor ehippers and grinders.		
Traps and drains	(1) Flush with water (2) Seour with rust remover. (3) Soak in a solution of citrie aeid. (4) Flush again	Follow all 4 steps	

H. Emergency procedures [15]

1. Minor spills involving no radiation hazards to personnel

1. Notify all other persons in the room at once
2. Permit only the minimum number of persons necessary to deal with the spill into the area
3. Confine the spill immediately
   Liquid Spills:
      Don protective gloves
      Drop absorbent paper on spill
   Dry Spills:
      Don protective gloves
      Dampen thoroughly, taking care not to spread the contamination
4. Notify the Radiological Safety Officer (RSO) as soon as possible
5. Decontaminate
6. Monitor all persons involved in the spill and cleaning
7. Permit no person to resume work in the area until a survey is made, and approval of the RSO is secured
8. Prepare a complete history of the accident and subsequent activity related thereto for the laboratory records

2. Major spills involving radiation hazards to personnel

1. Notify all persons not involved in the spill to vacate the room at once
2. If the spill is liquid and the hands are protected, right the container
3. If the spill is on the skin, flush thoroughly
4. If the spill is on clothing, discard outer or protective clothing at once
5. Switch off all fans
6. Vacate the room
7. Notify the Radiological Safety Officer (RSO) as soon as possible
8. Take immediate steps to decontaminate personnel involved
9. Decontaminate the area under the supervision of the RSO. (Personnel involved in the decontamination must be adequately protected)
10. Monitor all persons involved in the spill and cleaning to determine adequacy of decontamination
11. Permit no person to resume work in the area until a survey is made and approval of the RSO is secured
12. Prepare a complete history of the accident and subsequent activity related thereto for the laboratory records

3. Accidents involving radioactive dusts, mists, fumes, organic vapors, and gases

1. Notify all other persons to vacate the room immediately
2. Hold breath and close escape valves, switch off air-conditioning devices, etc., if time permits
3. Vacate room
4. Notify the RSO at once
5. Ascertain that all doors giving access to the room are closed
6. Report at once all known or suspected inhalations of radioactive materials
7. Evaluate the hazard and the necessary safety devices for safe reentry.
8. Determine the cause of contamination and rectify the condition
9. Decontaminate the area
10. Perform air survey of the area before permitting work to be resumed
11. Monitor all persons suspected of contamination
12. Prepare a complete history of the accident and subsequent activity related thereto for the laboratory records.

4. Injuries to personnel involving radiation hazard

1. Wash minor wounds immediately, under running water, while spreading the edges of the gash
2. Report all radiation accidents involving personnel (wounds, overexposure, ingestion, inhalation) to the Radiological Safety Officer as soon as possible
3. Call a physician qualified to treat radiation injuries at once
4. The person involved in the radiation injury should return to work unless the RSO or the attending physician do not permit it
5. Prepare a complete history of the accident and the subsequent activity related thereto for the laboratory records

5. Fires or other major emergencies

1. Notify all other persons in the room and building at once, and alert the fire department
2. Attempt to put out fires if radiation hazard is not immediately present
3. Notify Safety Division
4. Notify the Radiological Safety Officer
5. Govern fire-fighting or other emergency activities by the restrictions of the RSO
6. Following the emergency, monitor the area and determine the protective devices necessary for safe decontamination
7. Decontaminate
8. Permit no person to resume work without approval of the RSO
9. Monitor all persons involved in combating the emergency
10. Prepare a complete history of the emergency and subsequent activity related thereto for the laboratory records

I. United States Nuclear Regulatory Commission inspection and enforcement regional offices [16]

Region	Address	Telephone	
		Daytime	Nights and Holidays
I Connecticut, Delaware, District of Columbia, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont	Region I, USNRC Office of Inspection and Enforcement 631 Park Avenue King of Prussia, Pa. 19406	(215) 337-1150	(215) 337-1150
II Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, Panama Canal Zone, Puerto Rico, South Carolina, Tennessee, Virginia, Virgin Islands, and West Virginia	Region II, USNRC Office of Inspection and Enforcement 230 Peachtree St., N.W. Suite 1217 Atlanta, Ga. 30303	(404) 221-4503	(404) 221-4503
III Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin	Region III, USNRC Office of Inspection and Enforcement 799 Roosevelt Road Glen Ellyn, Ill. 60137	(312) 858-2660	(312) 858-2660
IV Arkansas, Colorado, Idaho, Kansas, Louisiana, Montana, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, Texas, Utah, and Wyoming	Region IV, USNRC Office of Inspection and Enforcement 611 Ryan Plaza Drive Suite 1000 Arlington, Texas 76012	(817) 334-2841	(817) 334-2841
V Alaska, Arizona, California, Hawaii, Nevada, Oregon, Washington, and U.S. territories and possessions in the Pacific	Region V, USNRC Office of Inspection and Enforcement 1990 N. California Blvd. Suite 202 Walnut Creek, Calif. 94596	(415) 486-3141	(415) 486-3141

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IV. Nuclear Counting Statistics [17]

A. Definition of symbols

N = total count	subscript g = gross counts
R = count rate	subscript b = background counts
t = counting time	subscript n = net count

B. Working formula for computing standard deviation

1. Total count (gross and background): $S_N = \sqrt{N}$

2. Count rate (gross and background): $s_R = \sqrt{\dfrac{R}{t}}$

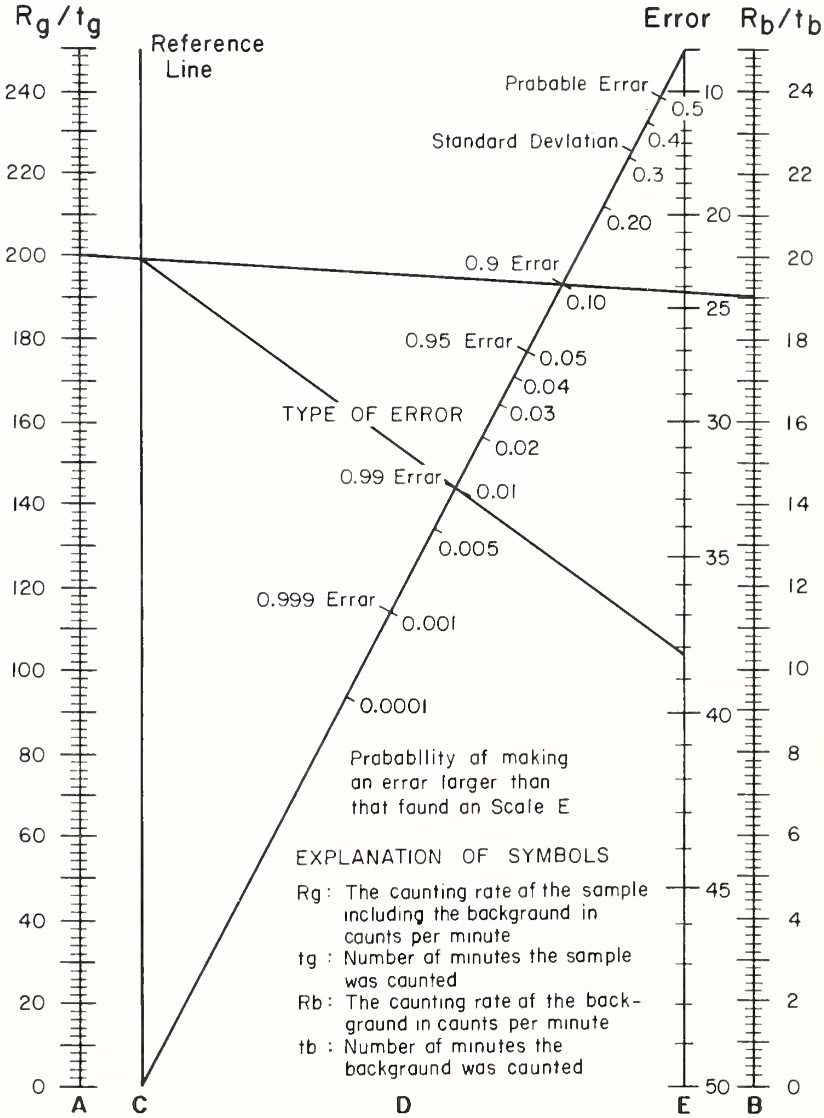
3. Net count rate: $s^2_{R_n} = s^2_{R_g} + s^2_{R_b}$

   or

$$s_{R_n} = \sqrt{\frac{R_g}{t_g} + \frac{R_b}{t_b}}$$

C. Nomogram for determining uncertainty in nuclear counting measurements

A useful chart which allows rapid estimation of the Poisson counting error, taking background into consideration, is given below. In the chart, R_g and R_b are the counting rates of the sample (including background) and the background, respectively; and t_g and t_b are the corresponding counting times. Draw a straight line from a point on Scale A corresponding to R_g/t_g to a point on Scale B corresponding to R_b/t_b. The intersection of this line with Reference Line C is noted; call it the Reference Point. A second straight line is drawn from the Reference Point through the point on the diagonal line (Scale D) that represents the desired confidence level and extended to intersect with Scale E. The magnitude of the error is read from the intersection of this second line with Scale E. For example, if 20,000 counts were collected in 10 minutes with a sample in place and 19 counts were observed in 1 minute of background counting, $R_g/t_g = (20{,}000/10)/10 = 200$ and $R_b/t_b = (19/1)/1 = 19$. A straight line is drawn through 200 on Scale A and 19 on Scale B. The Reference Point on line C is noted. A second line is drawn from the Reference Point through the point 0.99 on Scale D. The error is found to be 38 counts per minute on Scale E.



D. Optimum distribution of sample and background counting times

Under the constraint of a specified total counting time, the distribution of the time to yield the minimum uncertainty in the net count rate is given by

$$t_g/t_b = \sqrt{R_g/R_b} \ .$$

E. Uncertainty in count rate meter reading

The Poisson standard deviation of a single instantaneous reading of a count rate meter responding to a constant average disintegration rate is given by

$$S = \sqrt{\frac{r}{2T}} \text{ counts/s}$$

where r is the count rate in counts per second and T is the rate-meter time constant in seconds.

F. Chi-square test of goodness of fit

Pearson's chi-square test is useful for determining the likelihood that a set of observed data are random, e.g., successive counts of a constant radioactive source using the same instrument. The chi-square test determines the probability, P, that repitition of observations would show greater deviations from the assumed distribution than those observed. The statistic chi-square is defined as follows:

$$\chi^2 = \sum_i \frac{[(\text{observed value})_i - (\text{expected value})_i]^2}{(\text{expected value})_i}$$

For nuclear counting data, the expected value is the average count.

P values versus chi-squares are shown in the accompanying table for different degrees of freedom F. The number of degrees of freedom is the number of ways the observed distribution can differ from the assumed. For the Poisson distribution, $F{=}n{-}1$ where n is the number of observations.

The steps performing Pearson's chi-square test on nuclear counting data that follows a Poisson distribution are as follows:

a. Compute χ^2 from the observed data

b. Read the P value for the observed χ^2 and degrees of freedom. The closer P is to 0.5 the better the observed data fit the assumed distribution, because greater deviations than those observed would be expected 50% of the time due to chance alone. P values between 0.1 and 0.9 are usually taken as sufficient evidence that the observed distribution corresponds to the assumed one. A P value <0.02 means too much dispersion and $P>0.98$ means the data are too consistent for the observed data to be random.

Table of Chi-Square Values[a] [18]

Number of determinations (n)	0.99	0.95	0.90	P 0.50	0.10	0.05	0.01
3	0.020	0.103	0.211	1.386	4.605	5.991	9.210
4	0.115	0.352	0.584	2.366	6.251	7.815	11.345
5	0.297	0.711	1.064	3.357	7.779	9.488	13.277
6	0.554	1.145	1.610	4.351	9.236	11.070	15.086
7	0.872	1.635	2.204	5.348	10.645	12.592	16.812
8	1.239	2.167	2.833	6.346	12.017	14.067	18.475
9	1.646	2.733	3.490	7.344	13.362	15.507	20.090
10	2.088	3.325	4.168	8.343	14.684	16.919	21.666
11	2.558	3.940	4.865	9.342	15.987	18.307	23.209
12	3.053	4.575	5.578	10.341	17.275	19.675	24.725
13	3.571	5.226	6.304	11.340	18.549	21.026	26.217
14	4.107	5.892	7.042	12.340	19.812	22.362	27.688
15	4.660	6.571	7.790	13.339	21.064	23.685	29.141
16	5.229	7.261	8.547	14.339	22.307	24.996	30.578
17	5.812	7.962	9.312	15.338	23.542	26.296	32.000
18	6.408	8.672	10.085	16.338	24.769	27.587	33.409
19	7.015	9.390	10.865	17.338	25.989	28.869	34.805
20	7.633	10.177	11.651	18.338	27.204	30.144	36.191
21	8.260	10.851	12.443	19.337	28.412	31.410	37.566
22	8.897	11.591	13.240	20.337	29.615	32.671	38.932
23	9.542	12.338	14.041	21.337	30.813	33.924	40.289
24	10.196	13.091	14.848	22.337	32.007	35.172	41.638
25	10.856	13.848	15.659	23.337	33.196	36.415	42.980
26	11.524	14.611	16.473	24.337	34.382	37.382	44.314
27	12.198	15.379	17.292	25.336	35.563	38.885	45.642
28	12.879	16.151	18.114	26.336	36.741	40.113	46.963
29	13.565	16.928	18.939	27.336	37.916	41.337	48.278
30	14.256	17.708	19.768	28.336	39.087	42.557	49.588

[a] Usually tables in statistical texts give the probability of obtaining a value of χ^2 as a function of F, the number of degrees of freedom, rather than of n, the number of replicate determinations. In using such texts, the value of F should be taken as $n-1$.

V. In-Vivo Detector Systems

A. Terminology [19-22]

1. Response of a detector system is characterized by two parameters, efficiency (also commonly called sensitivity) and resolution.
2. Efficiency, E, for any system component is the ratio of the output events to the input events.
   a. Collimator efficiency, E_c: The ratio of the rate of primary photons passing through the total open collimator area which is exposing the detector to the rate of photons emitted by the source. E_c is dependent only on collimator construction geometry and does not include scatter effects.
   b. Geometric efficiency (planar source), E_g (cm^2): The ratio of the rate of photons passing through the collimator open area to the rate of photons emitted per unit area from a planar source placed on the collimator face.
   c. Intrinsic efficiency, E_i: The ratio of the counting rate output of the detector system to the photon rate incident on the detector (energy dependent).

d. Intrinsic detector efficiency, E_d: The ratio of the rate of useful ionizing events in the detector to the incident photon rate on the detector ($E_d = 1 - e^{-\mu x}$ where μ is the linear attenuation coefficient for the energy of interest and x is the detector thickness).

e. Data transfer efficiency, E_{Tr}: The ratio of the counting rate output to the rate of useful ionizing events in the detector. $E_I = E_d \cdot E_{Tr}$.

f. Photopeak efficiency, E_p: The ratio of the count rate output in a defined energy window around the primary photon energy to the incident photon rate on the detector.

3. Sensitivity, S, for any system is the ratio of measured count rate to the photons emitted per second for a particular source.

a. Point sensitivity, S_p: The ratio of the measured count rate to the photons emitted per second from a point source.

b. Line sensitivity, S_l (cm): The ratio of the measured count rate to the photons emitted per second per unit length of a long line source of uniform radioactivity.

c. Plane (area) sensitivity, S_A (cm^2): The ratio of the measured count rate to the photons emitted per sec per unit area from a large, thin plane source of uniform radioactivity.

4. Field of view (cm^2): The area of distribution of a radioactive source which may be seen by the detector (includes the umbra and penumbra).

a. Geometric field of view (cm^2): The area of distribution of radioactivity as seen by the detector neglecting penetration and scatter and is determined by the collimation geometry.

b. Radius of resolution (radius of field of view), R(cm): The radius of the circle in a plane at a given distance from the collimator from which photons must originate (in air) if they are to be incident on the detector (defined for focussing collimators only).

c. Geometric depth of focus λ (cm): The distance (total) inside and outside of the focal plane in which the diameter of the collimator umbral region is equal to the radius of resolution, R (focusing collimators only).

5. Line spread function, $L\ (x,z)$: The line spread function describes the variation of the line sensitivity, S_l, as a function of transverse position x in a plane perpendicular to the collimator axis at a distance z from the collimator. This function (generally bell-shaped) is a measure of the spatial resolution of the detector system.

6. Modulation transfer function, MTF (ν): Modulation transfer function is defined as the modulus of the Fourier transform of the line spread function:

$$\mathrm{MTF}\ (\nu) = \left| \int_{-\infty}^{\infty} L(x,z) e^{-i\nu x} dx \right| / \left| \int_{-\infty}^{\infty} L(x,z) dx \right|$$

The MTF characterizes the spatial frequency (ν) response of the system.

7. Figure of merit, $Q(\nu)$:

$$Q(\nu) \equiv \text{Efficiency } X \{\mathrm{MTF}(\nu)\}^2$$

8. Spatial resolution (overall), R_0 (cm): The minimum distance between two point sources containing equal amounts of radioactivity which will allow each of the points to be simultaneously distinguished by the imaging system:

$$R_0 = \sqrt{R_g^2 + R_s^2 + R_I^2}$$

a. Geometric component, R_g (cm): Determined by the geometric configuration of the holes in the collimator. Each collimator hole will define an individual radius of view for a given distance from the collimator.

b. Scatter component, R_s (cm): Scattered radiation produces an apparent increase in the radius of view which degrades the overall resolution. This scatter effect is a function of the source configuration, depth of the scattering medium, and pulse height analyzer setting.

c. Intrinsic component, R_I (cm): Reflects how accurately a given imaging system can localize an event which is recorded by the detector.

9. Minimum detectable activity, MDA (μCi):
MDA $\equiv (3/C)\sqrt{(r_b/t_b)}$ where C is the calibration factor (counts/(min·μCi)), r_b is the background counting rate (counts/min), and t_b is the background counting time (min).

10. Count information density, CID (cm^{-2}):
The number of counts recorded per unit object area.

11. Nonparalyzing deadtime, T(s): It is the time following any input event during which a system is insensitive. Recovery is not affected by additional input events which occur within time T after the initial event.

12. Paralyzing deadtime, τ(s): It is the time during which a system is unable to provide a second output pulse unless there is a time interval of at least τ between two successive events. Each input event prolongs the full recovery by an additional time τ.

B. Characteristics of detectors

1. Comparison of typical properties of semiconductor, gas filled, and NaI (Tl) detectors [23-25]

		Detector Type	
Parameter	Semiconductor	Gas filled	NaI(Tl)
Energy required to form an electron-hole or ion pair (eV)	3.5 (Si) 2.9 (Ge)	25-40	50 (~1000 to obtain a photoelectron at the photocathode of the PM tube)
Examples of FWHM (and % energy resolution) at 140 keV	~0.6 keV (0.4%)	5 keV (3.6%)	18 keV (13%)
Response time (s)	$\sim 10^{-9}$	10^{-3}	10^{-7}–10^{-6}

2. Basic properties of solid scintillators [26]

Material	Wavelength of Maximum Emission (nm)	Decay Constant (μs)*	Scintillation Cutoff Wavelength (nm)	Index of Refraction**	Density (g/cm³)	Hygro-scopic	γScintillation Conversion Efficiency (%)***
NaI(Tl)	410	.23	320	1.85	3.67	Yes	100
CaF_2(Eu)	435	.94	405	1.44	3.18	No	50
CsI(Na)	420	63	300	1.84	4.51	Yes	85
CsI(Tl)	565	1.0	330	1.80	4.51	No	45
^{6}LiI(Eu)	470-485[1]	1.4	450	1.96	4.08	Yes	35
TlCl(Be,I)	465	0.2	390	2.4	7.00	No	2.5
CsF	390	.005	220	1.48	4.11	Yes	5
BaF_2	325	63	134	1.49	4.88	No	10
$Bi_4Ge_3O_{12}$	480	.30	350	2.15	7.13	No	8
KI(Tl)	426	24/2.5[2]	325	1.71	3.13	Yes	24
$CaWO_4$	430	9-20[3]	300	1.92	6.12	No	14-18
$CdWO_4$	530	9-20[3]	450	2.2	7.90	No	17-20

* Room temperature, best single exponential decay constant, $I_0e^{-\lambda t}$

** At wavelength of maximum emission

*** Referred to NaI(Tl) with S-11 photocathode response

1 Primarily used for neutron detection

2 KI (Tl) has two scintillation decay components for γ excitation

3 Several decay components have been reported for the tungstates

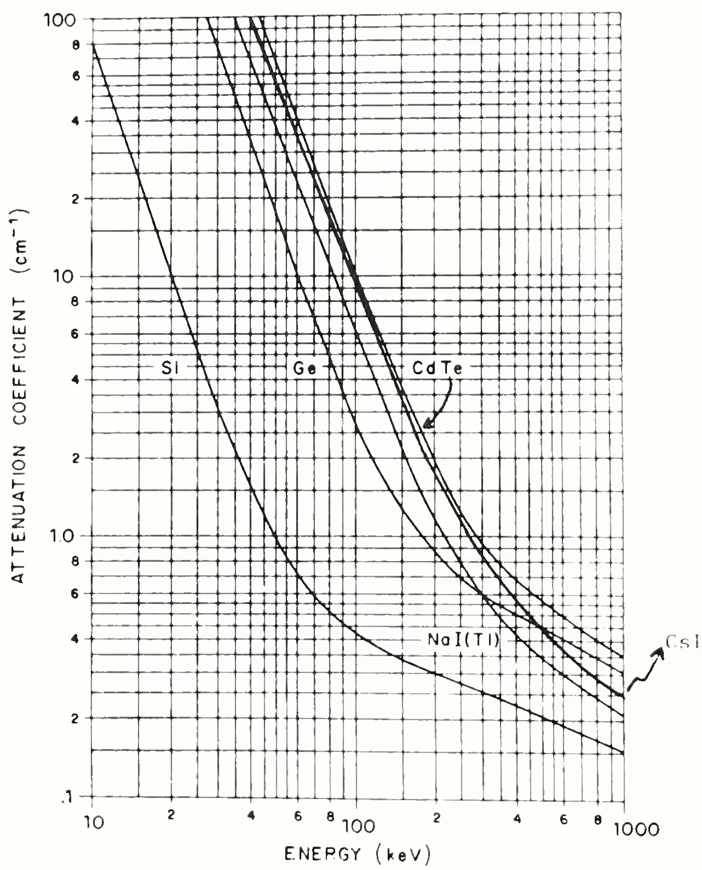
3. Mass attenuation coefficients for NaI (density = 3.67 g/cm³) [27]

Photon energy	Scattering: With coherent	Scattering: Without coherent	Photo electric	Pair production: Nuclear field	Pair production: Electron field	Total: With coherent	Total: Without coherent
MeV	cm²/g	cm²/g	cm²/g	cm²/g	cm²/g	cm²/g	cm²/g
1.00-02	2.53+00	1.65-01	1.36+02			1.39+02	1.36+02
1.50-02	1.69+00	1.62-01	4.57+01			4.74+01	4.59+01
2.00-02	1.23+00	1.59-01	2.11+01			2.23+01	2.12+01
3.00-02	7.48-01	1.54-01	6.70+00			7.45+00	6.86+00
3.32-02	6.60-01	1.52-01	5.03+00			5.69+00	5.19+00
*3.32-02	6.60-01	1.52-01	3.03+01			3.09+01	3.04+01
4.00-02	5.28-01	1.49-01	1.88+01			1.93+01	1.89+01
5.00-02	4.10-01	1.44-01	1.03+01			1.07+01	1.05+01
6.00-02	3.36-01	1.40-01	6.28+00			6.62+00	6.42+00
8.00-02	2.49-01	1.33-01	2.87+00			3.12+00	3.00+00
1.00-01	2.02-01	1.27-01	1.52+00			1.72+00	1.64+00
1.50-01	1.49-01	1.14-01	4.76-01			6.25-01	5.90-01
2.00-01	1.24-01	1.05-01	2.09-01			3.34-01	3.14-01
3.00-01	9.99-02	9.09-02	6.68-02			1.67-01	1.58-01
4.00-01	8.64-02	8.15-02	3.10-02			1.17-01	1.12-01
5.00-01	7.78-02	7.44-02	1.77-02			9.55-02	9.21-02
6.00-01	7.12-02	6.88-02	1.14-02			8.26-02	8.02-02
8.00-01	6.17-02	6.05-02	5.88-03			6.76-02	6.63-02
1.00+00	5.49-02	5.43-02	3.66-03			5.86-02	5.80-02
1.50+00	4.45-02	4.42-02	1.66-03	7.36-04		4.69-02	4.66-02
2.00+00	3.78-02	3.77-02	1.02-03	2.49-03		4.13-02	4.12-02
3.00+00	2.97-02	2.97-02	5.46-04	6.40-03	1.03-05	3.66-02	3.66-02
4.00+00	2.48-02	2.47-02	3.61-04	9.89-03	4.25-05	3.51-02	3.50-02
5.00+00		2.14-02	2.70-04	1.29-02	8.35-05		3.46-02
6.00+00		1.89-02	2.11-04	1.55-02	1.28-04		3.47-02
8.00+00		1.54-02	1.47-04	1.97-02	2.20-04		3.55-02
1.00+01		1.32-02	1.13-04	2.32-02	3.00-04		3.68-02

4. **Calculated intrinsic detector efficiencies for NaI (Tl) crystals (parallel beam of γ-rays) [21]**

γ-ray energy (MeV)	Thickness of the NaI (Tl) crystal 1/2 inch	1 inch	2 inches	4 inches
0.122	0.99	1.00	1.00	1.00
0.140	0.95	1.00	1.00	1.00
0.279	0.55	0.79	0.96	1.00
0.364	0.44	0.68	0.90	1.00
0.412	0.40	0.64	0.87	0.98
0.511	0.34	0.57	0.81	0.96
0.662	0.29	0.50	0.75	0.94
0.840	0.26	0.45	0.70	0.91
1.17	0.22	0.40	0.63	0.86
1.33	0.21	0.37	0.60	0.84
2.62	0.16	0.30	0.51	0.75
2.75	0.16	0.29	0.50	0.69

5. **Total linear attenuation coefficients for Ge, Si, CdTe, NaI (Tl), and CsI detectors [28,29] (total attenuation is defined here without coherent scattering or other minor effects)**



C. Deadtime considerations [30-31]

1. Nonparalyzing system

$$n = \frac{R}{1-RT}\ ,$$ with the two source method,

$$T \cong \frac{2(R_1 + R_2 - R_{12} - R_b)}{(R_1 + R_2 - R_b)\,(R_{12} - R_b)}, \qquad \text{for } R_1 \cong R_2\,.$$

2. Paralyzing system

$n = Re^{n\tau}$, with the two source method.

$$T \cong \frac{2R_{12}}{(R_1+R_2)^2} \ln \frac{(R_1+R_2)}{R_{12}}, \qquad \text{for } R_1 \cong R_2.$$

n is the true counting rate, R is the observed counting rate, and subscripts 1,2,12,b refer to source 1, source 2, combined source 1 and 2, and the background, respectively.

Measured deadtime performance of scintillation cameras was found to more closely approximate the paralyzable model than the nonparalyzable. 39 cameras yielded a range of 4.3 to 10 μs with a 20% window centered on ^{99m}Tc.

3. Survey of measured deadtime performance [30]

No. of cameras	Manufacturer	Models	Deadtime (μs) min.	max.	avg.
1	General Electric	Maxicamera			6.2
15	Ohio Nuclear	100, 110, 120			
		400, 410	5.7	10.1[a]	7.7
13	Picker	4–11, 4–12	4.3	7.6	5.3
		4–15, Dyna-Mo			
10	Searle	pho/gamma V	4.5[b]	5.4	4.9
		LFOV, LEM	5.2[c]	7.2	6.0
9	Older-generation cameras				
	Nuclear-Chicago	Various types	6.5	29.0	15.6
	Nuclear-Data				
	Picker				

[a] With tape-recording system.
[b] High-rate switch on.
[c] Normal rate.

D. Instrumentation

1. Rectilinear Scanners

a. Characteristics of focusing collimators [32-33] (see sec. 2f)

(i) Radius of resolution: $R = 2rf/a$ where r is the collimator hole radius (near the detector), f is the focal length, a is the collimator length.

(ii) Geometric efficiency (planar source):
$$E_g = \frac{N\pi r^2 R^2}{16(f+a)^2}$$

where N is the number of circular holes in a hexagonal array.

(iii) Plane sensitivity:
$$S_A \cong \frac{\pi r^2 R^2}{16\,(f+a)^2} \cdot \frac{3D^3}{4(2r+t)^2}\,E_p$$

where D is the detector diameter, t is the septa thickness, and E_p is the photopeak efficiency.

(iv) Geometric depth of focus: $\lambda = 2R(a+f)/D_0$
where D_0 is the maximum separation (between outer hole edges) of the collimator hole array of the face near the detector.

(v) Count information density:
$$\mathrm{CID} = \frac{(CR)}{(SS)} \cdot \frac{1}{(LS)}$$

where CR is the count rate (min^{-1}), SS is the scan speed (cm/min), and LS is the line spacing (cm). Optimal count rate densities are on the order of 800 to 1000 counts per cm^2.

2. Gamma cameras

a. Characteristics of parallel hole collimators [20,33,34,35] (see sec. 2f)

(i) Geometric spatial resolution:
$$R_g = 2r \cdot \frac{(a_e+b+c)}{a_e}$$

where r is the radius of the collimator holes, b is the distance from the collimator face to the object, c is distance between the collimator upper surface and the center of the detector (crystal) and a_e is the effective collimator length. $a_e \cong a - 2\mu^{-1}$ where a is the actual collimator length and μ is the total linear attenuation coefficient for the given material and energy ($\mu^{-1} \equiv$ mean free path).

(ii) Septal thickness considerations: The shortest distance that a photon may travel through the septa (w) should be equal to or greater than 3 times the mean free path. With w known, the septal thickness may be calculated: $t = 4rw/(a-w)$

(iii) Collimator efficiency:
$$E_c = K^2 \cdot \frac{16\,r^4}{a_e^2(2r+t)^2}$$

where t is the septum thickness and K is a constant which depends on the shape and distribution of the holes. Experimentally, $K \cong 0.28$ for square holes in a rectangular array and $K \cong 0.24$ for circular holes in a hexagonal array.

(iv) Geometric efficiency: $$E_g = \frac{NA_0 \pi r^4}{4A_d\, a^2_e}$$

where N is the number of holes, A_0 is the object area, and A_d is the area of the field of view of the detector.

(v) Plane sensitivity: $$S_A \cong \frac{\pi r^4}{4a^2} \cdot \frac{3D^2}{4(2r+t)^2} E_p$$

where D is the detector diameter and E_p is the photopeak efficiency.

b. Characteristics of pinhole collimators [35] (see sec. 2f)

(i) Geometric spatial resolution: $$R_g = \frac{(a+b)d_e}{a}$$

where a is the aperture (pinhole) to crystal central plane distance and d_e is the effective aperture diameter.

(ii) Overall resolution: $R_0 = \sqrt{R_g^2 + (\frac{b}{a}R_i)^2 + R_s^2}$

(iii) Effective diameter: $d_e = \{d(d+2\mu^{-1} \tan \alpha/2)\}^{\frac{1}{2}}$ where d is the aperture physical diameter and α is the angle defined by the collimator walls.

(iv) Collimator efficiency: $$E_c = \frac{d_e^2 \sin^3\theta}{16\, b^2}$$

c. Characteristics of converging collimators [34] (see sec. 2f)

(i) Geometrical spatial resolution:

$$R = \left[\frac{2r(a_e'+b+c)}{a_e'}\right]\left[\frac{1}{\cos\theta}\right]\left[1 - \frac{c+a_e'/2}{f+a_e'+c}\right]$$

where f is the focal length and $a_e'=(a-2\mu^{-1})/\cos\theta$

(ii) Collimator efficiency: $$E_c = \frac{K^2\, 16r^4}{a_e'^2\, (2r+t)^2} \cdot \frac{f^2}{(f-b)^2}$$

d. Characteristics of diverging collimators [36] (see sec. 2f)

(i) Geometric spatial resolution:

$$R_g = \left[\frac{2r(a_e'+b+c)}{a_e'}\right]\left[\frac{1}{\cos\theta}\right]\left[1+ \frac{a_e'+2c}{2f}\right]$$

where $a_e'=(a-2\mu^{-1})/\cos\theta$.

(ii) Collimator efficiency:

$$E_c = \left[\frac{K4r^2}{a_e'(2r+t)}\right]^2 \left[\frac{f+a+c}{f+a+b+c}\right]^2$$

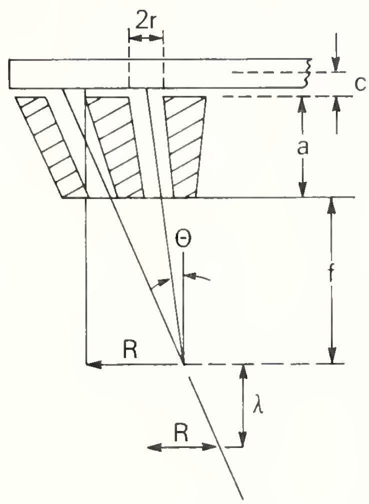
e. **Some characteristics of typical focusing collimators [37]**

Collimator type and measurement conditions (analyzer window settings)	Focal length (cm)	Plane sensitivity $\left(\frac{\text{cpm}\cdot\text{cm}^2}{\mu\text{Ci}}\right)$ (in focal plane)	FWHM (cm) (in focal plane)	MTF in the focal plane for 0.4 cycles per cm	Depth of field (cm)[a]
A. Low energy					
^{141}Ce (130–150 keV)	8.8	33,400	1.45	0.324	4.8
	8.8	4,600	0.59	0.834	4.9
	11.9	21,600	1.30	0.399	5.4
B. Medium energy					
^{131}I (344–384 keV)	10.5	36,000	2.08	0.081	4.4
	10.9	9,020	1.26	0.382	5.8
	8.7	28,000	1.02	0.443	3.8
C. High energy					
^{85}Sr (494–534 keV)	12.1	15,400	1.46	0.323	5.9
	12.6	7,530	0.86	0.319	6.2
	7.2	18,700	1.66	0.194	4.2

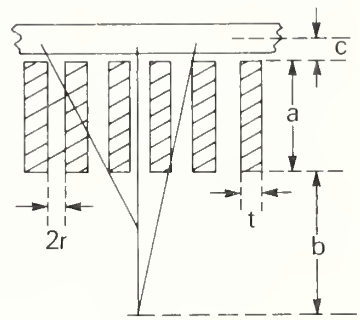
[a] The "Depth of field" is defined as the distance (axial) between points where the MTF is 60.7% of the peak MTF as given in the focal plane.

f. Geometry for the various collimators (modified from the references given)

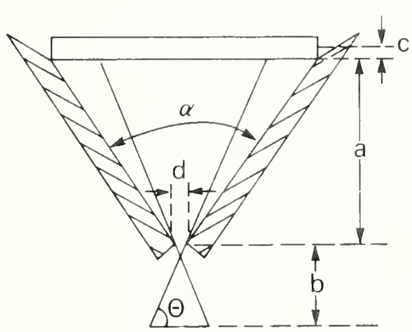
Focusing and Converging [32, 34]



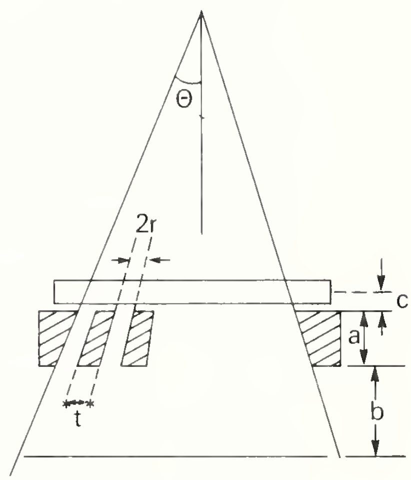
Parallel Hole [35]



Pinhole [35]



Diverging [36]



g. **Examples of experimental FWHM values of the line spread function for various physical pinhole diameters (^{99m}Tc at 20% window) [38]**

Pinhole diameter and insert material	FWHM (cm) Approximate distance from pinhole along central axis			Relative sensitivity
	6 cm	9 cm	13 cm	
3 mm (Lead)	0.30	0.36	0.46	1
5 mm (Lead + Tungsten)	0.41	0.50	0.60	2.4
9 mm (Lead + Tungsten)	0.63	0.82	0.95	6.9

h. **Characteristics of a gamma camera with small field of view [39]**

Parameter	5,000 cps[a]	50,000 cps[a]
Energy resolution		
(140 keV)	12.3%	12.4%
Intrinsic line spread function		
FWHM	3.8±0.1 mm	3.8±0.2 mm
FWTM	8.0±0.2 mm	8.5±0.3 mm
Linearity		
range[b]	+0.9%,-1.1%	
Uniformity		
range	+5.1%,-4.3%	+5.6%,-4.4%
max slope	0.7%/pixel	1.0%/pixel
Extrinsic line spread function[c]		
FWHM	9.5±0.2 mm	
FWTM	17.1±0.4 mm	

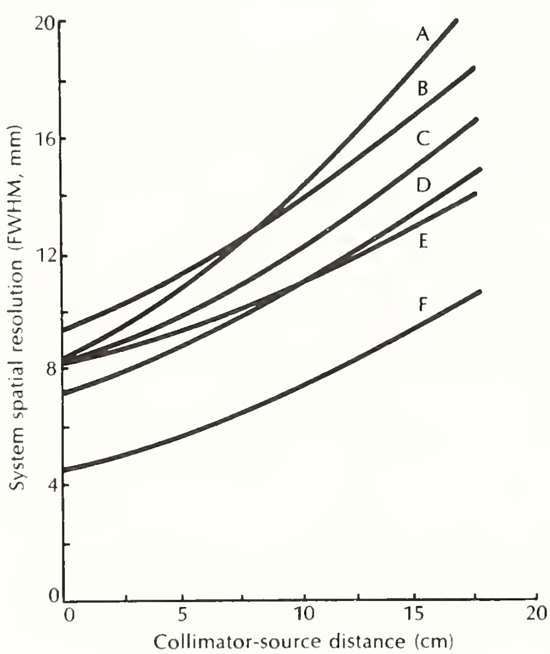
[a] As measured on the camera console scaler.
[b] Error in position in terms of % of the field of view.
[c] Data includes 48 samples of the line spread function within the field of view.

i. Typical characteristics of various commercially available gamma camera collimators [40]

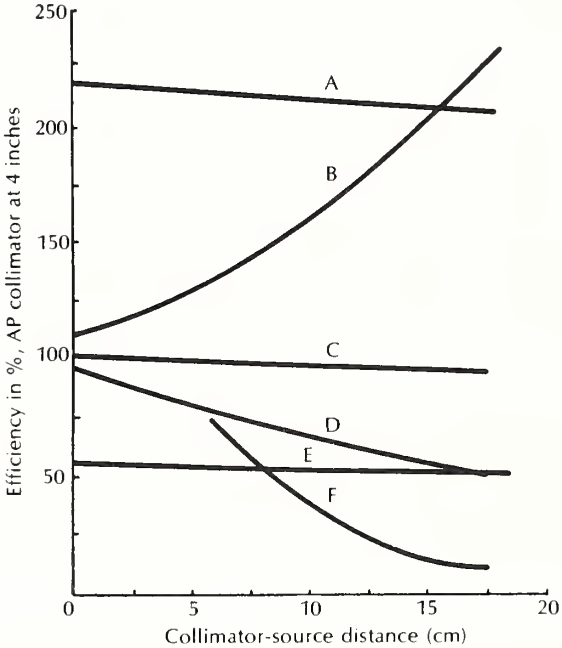
Collimator type	Length (cm)	Nominal number of holes	Suggested maximum energy (keV)	Sensitivity (counts/(min·mCi))	Collimator[a] FWHM (mm)	Diameter of field of view (cm)
Parallel hole	3.6	15,600	140	175,000 (^{99m}Tc)	9.1	38
Parallel hole	3.6	8,700	140	350,000 (^{99m}Tc)	13.0	38
Parallel hole	6.4	2,600	400	175,000 (^{131}I)	14.3	38
Converging	3.8	39,000	200	70,000 (^{99m}Tc) at 10 cm	3.2	26 at 9 cm
Converging	3.8	8,500	200	560,000 (^{99m}Tc) at 10 cm	8.1	26 at 9 cm
Parallel hole	2.5	40,000	140	108,500 (^{99m}Tc)	7.4	38

[a] For a source 10 cm from the collimator face for the isotope noted in the sensitivity column.

j. Effect of distance on system spatial resolution performance for various collimator types (A. High-sensitivity; B. diverging; C. all-purpose; D. converging; E. high-resolution; F. pinhole) [20]



k. Effect of collimator-planar source distance on geometrical efficiency for various collimator types in comparison with all-purpose (AP) collimator (A. High-sensitivity; B. converging; C. all-purpose; D. diverging; E. high-resolution; F. pinhole) [20]



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Notes

I. Physical Characteristics of Screens and Films [1,27]

A. Explanation of sections B1–B3

- The numbers in the body of the tables give the relative speeds of the various film—screen combinations, normalized to a value of 0.8 $(\mathrm{mR})^{-1}$ for par-speed screens used with XRP film, for peak potential of 80 kV (three phase), $\sim$35 mm aluminum filtration, "standard processing," and narrow beam geometry.
- The average gradient represents the slope of the portion of the characteristic curve (optical density vs log exposure) between net densities of 0.25 and 2.0 above base fog density.
- f_{50} and f_{10} represent those values of the spatial frequency (cycles/mm) at which the modulation transfer function is 0.5 and 0.1, respectively.

B. Tables of film-screen data

1. Relative speeds of Kodak X-Omatic and Du Pont screens and blue-sensitive film

Screens	f_{50}	f_{10}	Kodak XG	Du Pont Cronex 7	Kodak XRP	Du Pont Cronex 4	Du Pont Cronex 6	Du Pont Cronex 6+	3M Type R	Kodak XS	Kodak XR
Film average gradient			3.0	3.0	2.8	3.0	2.2	2.6	2.4	2.6	2.4
X-Omatic fine ($BaPbSO_4$) Yellow Dye	3.1	9.7	0.15		0.3					0.45	0.6
X-Omatic regular ($BaSrSO_4$:Eu)	1.5	4.8	0.8		1.6					2.4	3.2
Detail ($CaWO_4$) Yellow Dye	2.5	10.5	0.1		0.2					0.3	0.4
Fast Detail ($CaWO_4$)	1.8	6.5	0.2		0.4					0.6	0.8
Par ($CaWO_4$)	1.4	5.0	0.4		0.8					1.2	1.6
Hi-speed ($BaPbSO_4$)	1.0	3.2	0.6		1.2					1.8	2.4
Hi-plus ($CaWO_4$)	1.1	3.3	0.8		1.6					2.4	3.2
Lightning Plus ($CaWO_4$)	0.9	3.2	1.2		2.4					3.6	4.8
Quanta II (BaFCl)	1.1	3.3	1.6		3.2					4.8	6.4
Quanta III (La_2O_2Br)	0.9	3.0	3.2		6.4					9.6	12.8

2. Relative speeds of Kodak and 3M rare-earth screens and green-sensitive film

Screens	Film: f_{50}	f_{10}	Kodak Ortho G (SO-225)	3M XD	3M XM
average gradient			2.4	2.9	2.2
Kodak Lanex Fine ($La_2O_2S{:}Tb$ $Gd_2O_2S{:}Tb$)	2.1	7.8	1.0	1.3	3.3
3M Alpha 4 ($La_2O_2S{:}Tb$ $Gd_2O_2S{:}Tb$) Pink Dye	1.7	5.8	1.5	2.0	5.0
3M Alpha 8 ($La_2O_2S{:}Tb$ $Gd_2O_2S{:}Tb$)	1.2	3.3	3.0	4.0	10.0
Kodak Lanex Regular (SO-359) ($La_2O_2S{:}Tb$ $Gd_2O_2S{:}Tb$)	1.1	3.3	3.5	4.7	11.7

3. Relative speeds of U.S. Radium and G.E. rare-earth screens and blue-sensitive film

Screens	Film: f_{50}	f_{10}	Kodak XG	Du Pont Cronex 7	Kodak XRP	Du Pont Cronex 4	Du Pont Cronex 6	Du Pont Cronex 6+	3M Type R	Kodak XS	Kodak XR
average gradient			3.0	3.0	2.8	3.0	2.2	2.6	2.4	2.6	2.4
U.S.R. Rarex BG Detail (75% $Gd_2O_2S{:}Tb$ 25% $Y_2O_2S{:}Tb$)	1.4	3.9	0.5				1.0			1.5	2.0
U.S.R. Rarex BG Mid-speed (75% $Gd_2O_2S{:}Tb$ 25% $Y_2O_2S{:}Tb$)	1.1	3.5	1.0				2.0			3.0	4.0
U.S.R. Rarex BG Hi-speed (75% $Gd_2O_2S{:}Tb$ 25% $Y_2O_2S{:}Tb$)	0.8	2.3	2.0				4.0			6.0	8.0
G.E. Blue Max 1 (La_2O_2Br)	1.5	4.3	1.0				2.0			3.0	4.0
G.E. Blue Max 2 (La_2O_2Br)	1.2	3.2	2.0				4.0			6.0	8.0

II. Machine Output Data

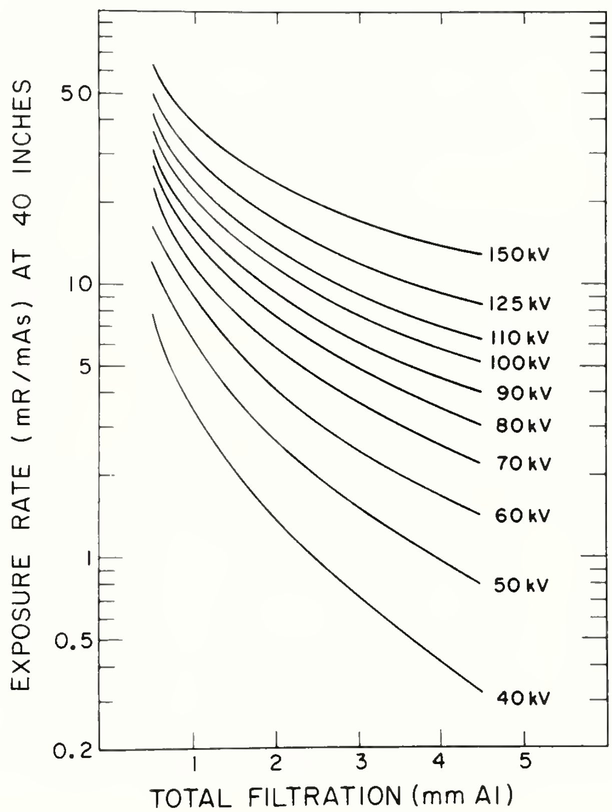
A. Average exposure rates

1. Average exposure rates as a function of peak tube potential and distance[a] [2]

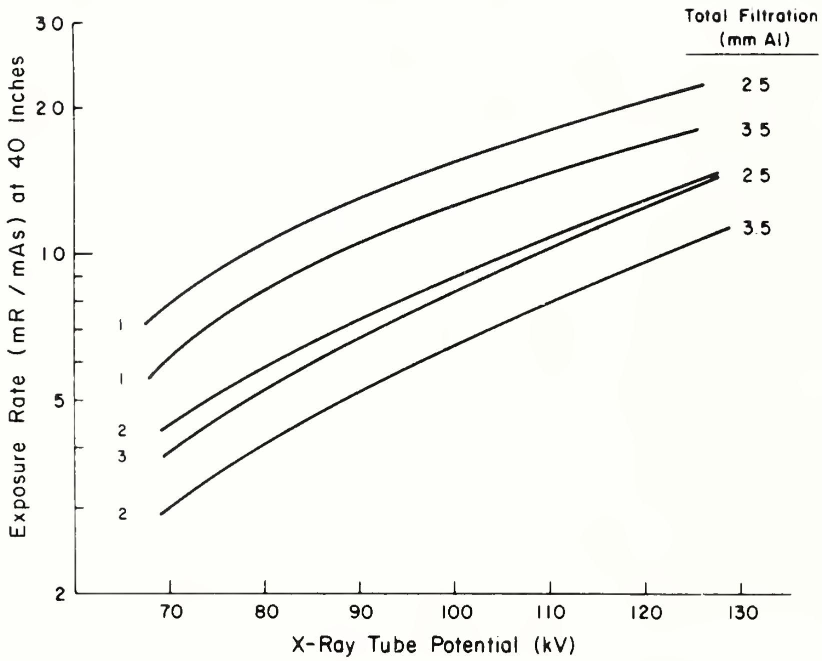
Distance from source to point of measurement		Peak tube potential (kV) 40	60	70	80	90	100	125
in	cm	Roentgens per 100 milliampere seconds						
12	30	1.8	2.8	4.2	5.8	8.0	9.8	15.2
18	46	0.8	1.3	1.8	2.5	3.4	4.2	6.7
24	61	0.4	0.7	1.1	1.4	1.9	2.3	3.8
39	100	0.2	0.3	0.4	0.5	0.7	0.9	1.4
54	137	0.1	0.1	0.2	0.3	0.4	0.5	0.7
72	183	0.1	0.1	0.1	0.2	0.2	0.3	0.4

[a] Measured in air with total filtration equivalent to 2.5 mm aluminum; single phase, full wave rectification.

2. Calculated exposure rates as a function of peak tube potential and total filtration (full wave rectification) [3]



3. Exposure rates as a function of peak tube potential [2,3,4]



Curves 1 were obtained [4] with an x-ray source that showed intensity fluctuations of ±15% about the mean (three phase). Curves 2 were calculated [3] for full-wave rectification (single phase). Curve 3 is a graphic representation of data tabulated in [2] (single phase).

B. Beam quality measurement

1. Half-value layers as a function of filtration and tube potential for diagnostic units[a] [5]

Total Filtration mm Al	Peak Potential (kV) 30	40	50	60	70	80	90	100	110	120
	Typical half-value layers in millimeters of aluminum									
0.5	0.36	0.47	0.58	0.67	0.76	0.84	0.92	1.00	1.08	1.16
1.0	0.55	0.78	0.95	1.08	1.21	1.33	1.46	1.58	1.70	1.82
1.5	0.78	1.04	1.25	1.42	1.59	1.75	1.90	2.08	2.25	2.42
2.0	0.92	1.22	1.49	1.70	1.90	2.10	2.28	2.48	2.70	2.90
2.5	1.02	1.38	1.69	1.95	2.16	2.37	2.58	2.82	3.06	3.30
3.0	—	1.49	1.87	2.16	2.40	2.62	2.86	3.12	3.38	3.65
3.5	—	1.58	2.00	2.34	2.60	2.86	3.12	3.40	3.68	3.95

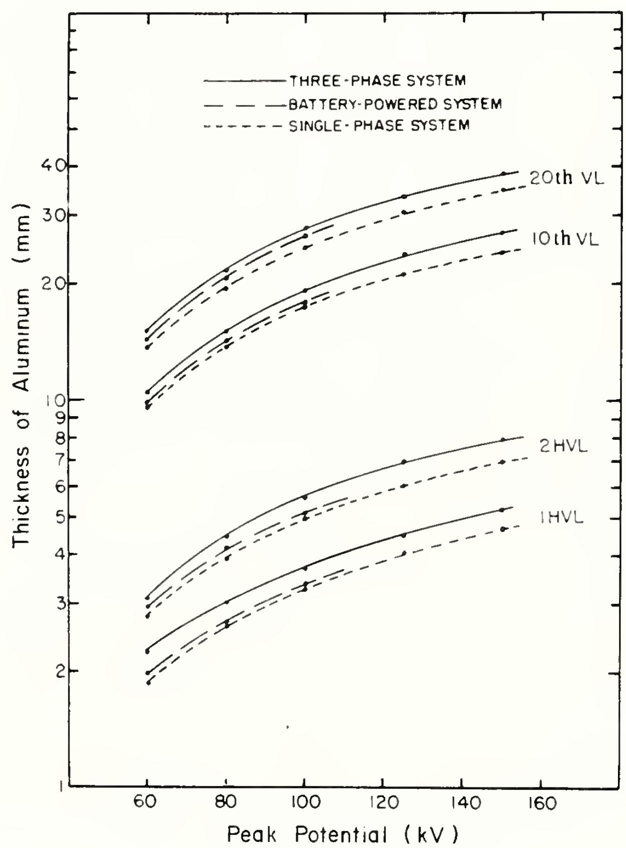
[a] For full-wave rectified, single phase, potential. Derived from [6] by interpolation and extrapolation.

2. Half-value layers as a function of tube potential for three-phase generators

Total Filtration mm Al	Peak Potential (kV) 60	70	80	90	100	110	120	130	140
	Half-value layers in millimeters of aluminum								
2.5[a]	2.2	2.4	2.7	3.1	3.3	3.6	4.0	—	—
3.0[b]	2.3	2.6	3.0	3.3	3.6	4.0	4.3	4.6	5.0
3.5[a]	2.6	2.9	3.2	3.6	3.9	4.3	4.6	—	—

[a]Estimated from [2] and [7]
[b]From [7]

3. Unique value layers in aluminum as a function of peak tube potential and waveform [7]



III. Patient Dose Calculation

A. Tissue-Air Ratios (TAR)

1. Dose/exposure ratios[a] (TAR•f) as a function of peak potential and depth. (40×40 cm field; 80 cm SID; three phase, ±15% ripple) [4]

Total Filtration = 2.5 mm Al

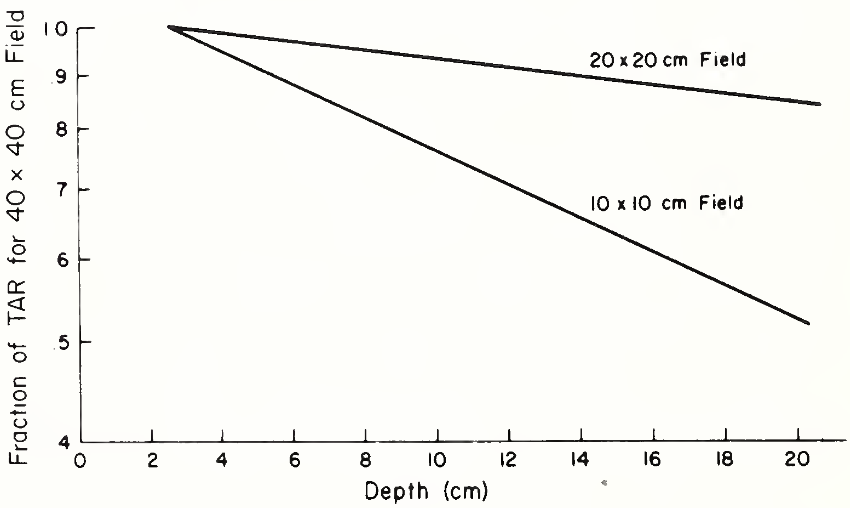
Depth (cm)	kV 70	80	90	100	120
0	1.02	1.09	1.12	1.14	1.15
2	1.00	1.07	1.10	1.13	1.15
4	0.709	0.794	0.834	0.878	1.00
6	0.501	0.580	0.621	0.665	0.742
8	0.354	0.423	0.463	0.504	0.573
10	0.250	0.309	0.345	0.382	0.443
12	0.177	0.226	0.257	0.289	0.342
14	0.125	0.165	0.192	0.219	0.264
16	0.088	0.120	0.143	0.166	0.204
18	0.062	0.088	0.107	0.126	0.158
20	0.044	0.064	0.080	0.095	0.122

Total Filtration = 3.5 mm Al

Depth (cm)	kV 70	80	90	100	120
0	1.07	1.10	1.12	1.14	1.15
2	1.06	1.09	1.11	1.15	1.20
4	0.791	0.845	0.904	0.955	1.09
6	0.566	0.625	0.679	0.726	0.813
8	0.406	0.461	0.510	0.552	0.630
10	0.291	0.340	0.383	0.420	0.489
12	0.208	0.250	0.288	0.320	0.379
14	0.149	0.185	0.217	0.243	0.294
16	0.107	0.136	0.163	0.185	0.228
18	0.077	0.100	0.122	0.141	0.177
20	0.055	0.074	0.092	0.107	0.137

[a] Absorbed dose to a given point in water (rad) per unit of exposure (*R*) at the same point in the absence of water. The *f*-factor is taken to be 0.875.

2. Effect of field size on TAR [4]



Tissue-air ratios for 10×10 and 20×20 cm fields expressed as fractions of the TAR's for a 40×40 cm field. The effect of field size on TAR's is independent of peak potential from 70 to 120 kV, and filtration from 2.5 to 3.5 mm Al.

B. Backscatter Factors

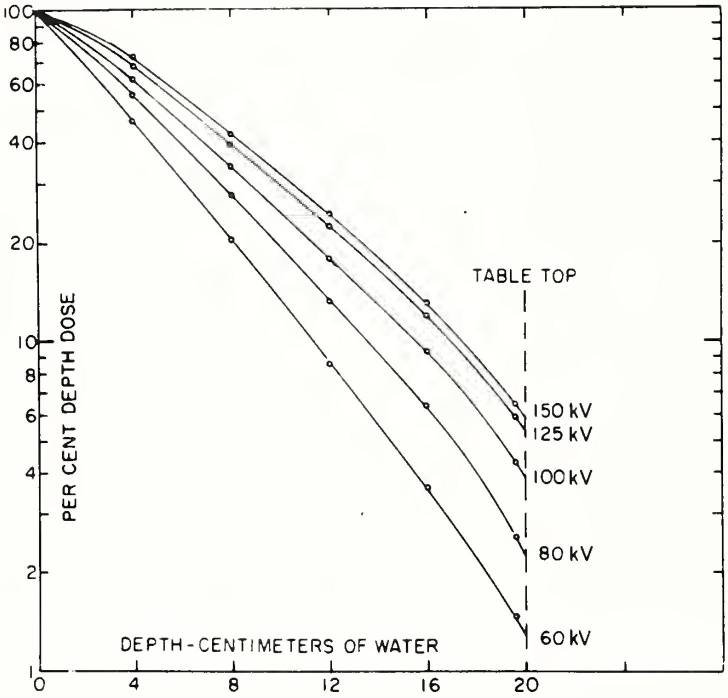
1. Variation of backscatter factors with field diameter and half-value layer in mammography. (Each entry is subject to an estimated error of 0.25.) [8]

Field diameter (cm)	Half-value layer (mm Al) 0.40	0.55	0.89	1.29
2	1.06	1.09	1.11	1.14
5	1.07	1.12	1.14	1.19
10	1.07	1.13	1.17	1.24
15	1.08	1.14	1.19	1.26
25	1.08	1.15	1.20	1.27

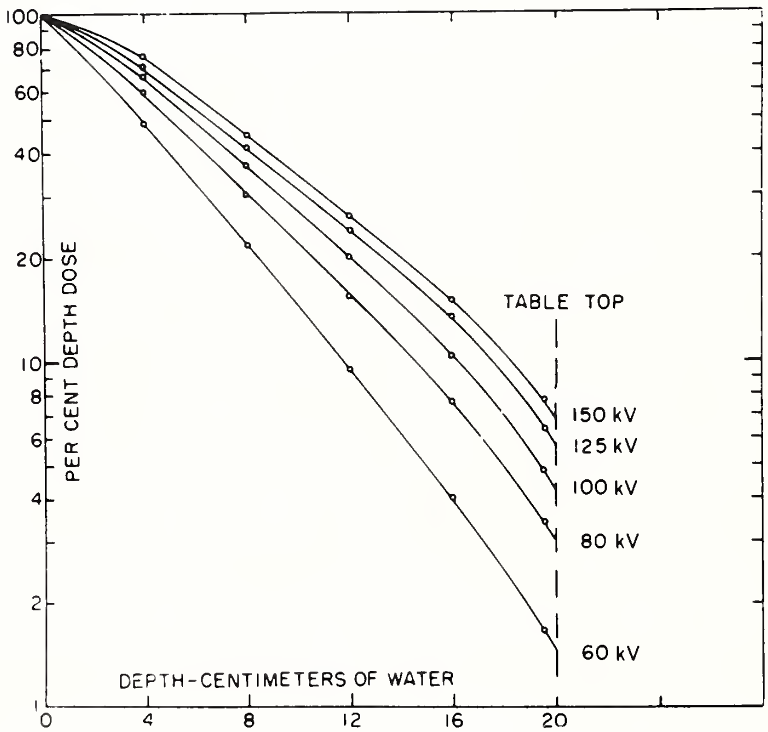
2. Backscatter factors as a function of peak tube potential. (Single phase, full wave rectification) [9]

kV	Backscatter Factor, Field size (cm): 20×25	35×43
40	1.16	1.16
60	1.27	1.27
80	1.34	1.35
100	1.38	1.40
130	1.41	1.45
150	1.42	1.46

C. Central axis depth doses in water [7]



Central axis depth dose in water: single-phase system, 30-inch source-to-skin distance, 14×17-inch field at 40 inches.



Central axis depth dose in water: three-phase system, 30-inch source-to-skin distance, 14×17-inch field at 40 inches.

D. Estimated patient doses

1. Estimated mean dose indexes and technique factors by type of exam/projection[a] [10]

	Exposure at skin entrance without backscatter (mR)	Gonadal dose M (mrad)	Gonadal dose F (mrad)	Red Bone marrow dose (mrad)	Thyroid dose (mrad)	Exposure conditions kV (peak) Mean (range)	Exposure conditions mAs Mean (range)
Chest (P/A)	22±0.9	<0.5	<0.5	1.9±0.1	0.5	80 (40–150)	12 (1–100)
Skull (lateral)	241±23	<0.5	<0.5	6.9±0.7	45±8	72 (48–94)	50 (5–150)
Abdomen (KUB) (A/P)	644±24	13.7±1.8	146±6.7	23.4±1.2	<0.5	78 (45–125)	601 (4–2471)
Retrograde Pyelogram (A/P)	722±74	17.2±2.9	161±17.7	26.4±3.1	<0.5	77 (55–106)	91 (6–300)
Thoracic spine (A/P)	724±271	<0.5	0.7±0.8	18.8±3.2	65.7±55.7	75 (57–90)	82 (12–200)
Cervical spine (A/P)	238±22	<0.5	<0.5	3.2±1.3	157±9.1	69 (40–100)	48 (2–200)
Lumbo-sacral spine (A/P)	808±44	13.2±1.3	145±6.7	19.7±0.9	<0.5	77 (55–106)	112 (15–450)
Full spine (A/P)	315±46	23.9±15.1	40.7±8.4	18.5±2.0	136±30	79 (64–96)	173 (20–400)
Foot (D/P)	263±43					61 (45–90)	18 (1–80)
Dental bitewing	462±20					71 (40–110)	7 (1–54)
Dental periapical	513±67					71 (40–110)	7 (1–75)
Dental cephalometric (Lateral)	356±44	<0.5	<0.5	1.5±0.2	15.9±1.8	81 (60–98)	18 (3–60)

[a] Determined by the Nationwide Evaluation of X-Ray Trends program, from 1/1/73—12/31/76 for all states, for a patient having the following body part/thickness: head/15 cm; neck/13 cm; thorax/23 cm; abdomen/23 cm; and foot/8 cm.

2. Exposures from mammographic units at Breast Cancer Detection Demonstration Projects[a] [11]

Detector	Target-filter	No. of units	Average exposure[b] (R)
Film-screen (Lo-dose; min R)	Mo-Mo	10	0.88±0.3
	Other than Mo	2[c]	0.5
Xerox	W-None	5	1.27±0.5
	W-Al	29	1.23±0.44
	Mo-Al	5	1.26±0.6
	Other than above	2	1.44
Xerox (neg. mode)		4[c]	2.2[c]
Non-screen film	Any	4[c]	4.6[c]

[a] 7/1/76—6/30/77.
[b] Average exposure (Roentgens) per image to the surface of a 6 cm breast.
[c] 7/1/73—6/30/76.

3. Dosimetric estimates for routine examinations of the newborn [12]

Examination	AP chest	AP abdomen	Lateral chest	Lateral abdomen
Screen/film[a]	Par/RP	Par/RP	Par/XD	Par/RP
Peak potential (kV)	62	62	68	68
Current (mA)	100	100	100	100
Time (s)	1/30	1/30	1/30	1/30
Generator output at 61 cm from focal spot (mR)	13	13	16	16
Exposure at anatomical site per radiograph (mR)				
Entrance chest	5.9	0.23	7.8	0.2
Exit chest	2.1	0.20	3.7	0.16
Entrance abdomen	1.8	6.5	0.19	8.7
Midline abdomen	0.3	3.9	0.36	4.5
Exit abdomen	0.14	1.5	0.14	1.3
Gonads	0.08	3.5	0.08	3.9
Thyroid	3.5	0.09	4.3	0.13

[a] Exposures may be estimated for other screen film combinations by using the relative speed values in section I of chapter three.

4. Embryo (uterine) doses for selected x-ray projections (mrad/R)[a,b,e] [5]

Projection	View	SID (inches)	Image Receptor Size (inches)[c]	Beam Quality (HVL, mm Al) 1.5	2.0	2.5	3.0	3.5	4.0
Pelvis, lumbopelvic	AP	40	17 × 14	142	212	283	353	421	486
	LAT	40	14 × 17	13	25	39	56	75	97
Abdominal[d]	AP	40	14 × 17	133	199	265	330	392	451
	PA	40	14 × 17	56	90	130	174	222	273
	LAT	40	14 × 17	13	23	37	53	71	91
Lumbar Spine	AP	40	14 × 17	128	189	250	309	366	419
	LAT	40	14 × 17	9	17	27	39	53	68
Hip	AP (one)	40	10 × 12	105	153	200	244	285	324
	AP (both)	40	17 × 14	136	203	269	333	395	454
Full Spine (Chiropractic)	AP	40	14 × 36	154	231	308	384	457	527
Urethrogram Cystography	AP	40	10 × 12	135	200	265	327	386	441
Upper G.I.	AP	40	14 × 17	9.5	16	25	34	45	56
Femur (one side)	AP	40	7 × 17	1.6	3.0	4.8	6.9	9.4	12
Cholecystography	PA	40	10 × 12	0.7	1.5	2.6	4.1	6.0	8.3
Chest	AP	72	14 × 17	0.3	0.7	1.3	2.0	3.1	4.3
	PA	72	14 × 17	0.3	0.6	1.2	2.0	3.0	4.5
	LAT	72	14 × 17	0.1	0.3	0.5	0.8	1.2	1.8
Ribs, Barium Swallow	AP	40	14 × 17	0.1	0.3	0.5	0.9	1.4	2.0
	PA	40	14 × 17	0.1	0.3	0.5	0.9	1.5	2.2
	LAT	40	14 × 17	0.03	0.08	0.2	0.3	0.4	0.6
Thoracic Spine	AP	40	14 × 17	0.2	0.4	0.8	1.4	4.1	3.0
	LAT	40	14 × 17	0.04	0.1	0.2	0.4	0.5	0.8
Skull, Cervical Spine, Scapula, Shoulder, Humerus		40		<.01	<.01	<.01	<.01	<.01	<.01

[a] Average dose to the uterus (mrad) for 1 roentgen entrance skin exposure without backscatter.
[b] From [13].
[c] Field size is collimated to the image receptor size.
[d] Includes: Retrograde Pyelogram, KUB, Barium Enema, Lumbosacral Spine, IVP, Renal Arteriogram.
[e] This table is suggested only for average-sized women in the first two months of pregnancy.

IV. Scatter

A. Definitions

1. Scatter Fraction$=s/(s+p)$, where s and p are the intensities of scattered and primary radiation, respectively.
2. Thickness (g/cm^2) = Thickness (cm)$\times$Density (g/cm^3).
3. Air Gap = Distance between phantom and radiation receptor.

B. Scatter Fractions in general radiography

1. Dependence on field size and phantom thickness [14]

Scatter Fraction[a]

Field size (cm×cm)	Phantom thickness (g/cm^2) 5.5	9	13	18.5	22	27.5
5×5	0.36	0.42	0.48	0.52	0.54	0.57
10×10	0.44	0.54	0.61	0.68	0.72	0.76
20×20	0.49	0.62	0.71	0.78	0.82	0.86
30×30	0.50	0.63	0.74	0.80	0.83	0.88

[a] At a peak potential of 78 kV (single phase), 2.1 mm of Al HVL, measured directly beneath the center of the phantom (no air gap).

2. Dependence on field size, phantom thickness, and air gap [14]

Scatter Fraction[a]

Field size (cm×cm)	Phantom thickness (g/cm^2)	Air gap (cm) 5	10	20	30	40	50
5×5	9	0.22	0.17	0.11	0.08	0.08	0.07
	18.5	0.34	0.24	0.13	0.12	0.12	0.12
10×10	9	0.41	0.32	0.20	0.16	0.13	0.12
	18.5	0.56	0.46	0.31	0.25	0.19	0.18
20×20	13	0.65	0.58	0.45	0.37	0.31	0.27
	22	0.77	0.69	0.60	0.51	0.45	0.38
30×30	18.5	0.79	0.75	0.65	0.56	0.50	0.44
	27.5	0.86	0.84	0.78	0.71	0.63	0.59

[a] At a peak potential of 78 kV (single phase), 2.1 mm of Al HVL, fixed 400 cm source-to-phantom (rear surface) distance.

3. Dependence on beam quality

Typically, a 4–10% increase in the scatter fraction was observed as the peak potential was changed from 60 to 105 kV for polychromatic beams [14], or as the photon energy was changed from 32 to 69 keV for mono-energetic x-rays [15].

C. Scatter Fractions in mammography

1. Dependence on field size and phantom thickness [16]

Scatter Fraction[a]

Field size[b] (cm)	Phantom thickness (g/cm^2) 3.6	4.8	6.0	7.1
4	0.24			0.35
6	0.27			0.39
10	0.28			0.44
14	0.29	0.35	0.42	0.46

[a] Measured at a peak potential of 32 kV for a Lucite phantom. Little or no dependence was observed as the peak potential was varied from 27 kV to 42 kV.
[b] Diameter of circular radiation field.

V. Grids

A. Definitions

1. Transmission (T)
   transmission of primary radiation, $T_p = p'/p$
   transmission of scattered radiation, $T_s = s'/s$
   transmission of total radiation, $T_t = (p'+s')/(p+s)$

where p' and s' and p and s are the intensities of primary and scattered radiation with and without the grid, respectively.

2. Bucky Factor (B)
   the total incident radiation divided by the total transmitted radiation, $B = 1/T_t$.

3. Selectivity(Σ)
   the transmission of primary radiation divided by the transmission of scattered radiation, $\Sigma = T_p/T_s$.

4. Contrast Improvement Factor (K)
   the ratio of x-ray contrast with grid, divided by the x-ray contrast without grid, $K = (1+s/p)/(1+s'/p') = T_p{\cdot}B$.

B. Minimum performance data for fibre and aluminum interspace grids [17] (measured with 20 cm thick, 30 cm × 30 cm polystyrene phantom)

	Maximum Bucky factors[b]				Minimum selectivities[c]				Minimum contrast Improvement factors[d]			
	60 kV[a]		100 kV[a]		60 kV[a]		100 kV[a]		60 kV[a]		100 kV[a]	
Ratio	Fibre	Al	Fibre	Al	Fibre	Al	Fibre	Al	Fibre	Al	Fibre	Al
4:1	3.90		3.10		3.60		2.50		2.10		1.80	
5:1	4.70	5.10	3.70	3.70	5.00	5.00	3.10	2.90	2.50	2.50	2.00	2.00
6:1	5.20	5.50	4.00	4.00	5.90	5.70	3.60	3.30	2.90	2.60	2.30	2.20
8:1	6.40	7.40	5.20	5.20	8.80	8.30	5.10	4.70	3.20	3.10	2.70	2.60
10:1		8.50		6.00		11.70		6.00		3.60		3.00
12:1	7.60	9.80	6.40	7.00	13.50	14.80	8.10	7.80	3.70	3.80	3.40	3.30
16:1	8.70		7.80		19.50		12.50		4.20		3.90	
5:1 Crossed	9.50		7.00		19.90		7.00		3.90		3.10	
6:1 Crossed		13.10		8.30		26.90		8.30		4.20		3.30
8:1 Crossed	13.30		10.60		65.50		15.60		4.90		4.20	

[a] Peak potential.
[b] Typical Bucky factors are from 5 to 13% less [18].
[c] Typical selectivities are from 5 to 18% greater [18].
[d] Typical contrast improvement factors are from 7 to 20% greater [18].

VI. X-Ray Tubes [19]

A. Radiation field coverage[a] for selected target angles and source-image distances (SID)

	Target angle				
SID	7°	10°	11°	12°	15°
91.4 cm	192.2 cm	29.0 cm	32.2 cm	35.5 cm	45.6 cm
101.6 cm	21.4 cm	32.3 cm	35.8 cm	39.5 cm	50.7 cm
121.9 cm	25.6 cm	38.6 cm	43.0 cm	47.4 cm	60.8 cm
182.9 cm	38.4 cm	57.9 cm	64.5 cm	71.1 cm	91.2 cm
36 in	7.6 in	11.4 in	12.7 in	14.0 in	18.0 in
40 in	8.4 in	12.7 in	14.1 in	15.6 in	19.9 in
48 in	10.0 in	15.2 in	16.9 in	18.7 in	23.9 in
72 in	15.1 in	22.8 in	25.4 in	28.0 in	25.9 in

[a] Coverage $= 2 \cdot \mathrm{SID} \cdot \tan\theta$, $\theta \equiv$ radiation angle $\equiv$ target angle $-1°$.

B. Typical focal spot combinations and applications

Application	Target Angle	Disk diameter (mm)	Focal combination (mm)
High power, general radiography	15°	75–100	1.0–2.0
Angiography and general radiography	12°	100–125	0.6–1.2
Under-table fluoroscopy and screen spot film	10°	100	0.3–1.0,0.6–1.2
Under-table fluoroscopy and image intensifier spot film camera			
9 in image intensifier	10°	100	0.3–1.0
6 in image intensifier	7°	100	0.3–0.6
Chest, 6 ft–10 ft SID	10°–12°	100	0.6–1.2
Mammography (Mo or W targets, low absorption window)	12°	75	0.6–1.2

C. Focal spot measurement

1. Blurring frequency of star resolution pattern

$$f = \left(\frac{\pi}{180°}\right)\left(\frac{\theta \cdot D}{M-1}\right),$$

where f=focal spot size, θ =angle of spoke (wedge angle) in degrees, D=imaged diameter of blurring frequency perpendicular to the focal spot dimension measured and M=magnification factor of the resolution pattern. It is recommended that a nominal magnification factor of $M=1+1/\xi$ be employed where ξ is the focal spot size (mm) specified by the x-ray tube manufacturer.

2. Recommended geometry of pinhole cameras

Nominal dimensions of focal spot, f (mm)	Nominal diameter of pinhole diaphragm (mm)	Magnification factor
$0.3<f\leqslant 1.2$	0.030	2
$1.2<f\leqslant 2.5$	0.075	2
$2.5<f$	0.100	1

3. NEMA[a]-recommended test procedures and tolerances

A pinhole camera is recommended for measuring x-ray focal spots having a nominal size greater than 0.3 mm. A star resolution pattern is recommended for focal spots having a size equal to or less than 0.3 mm.

Test voltage and current

Maximum rated tube voltage, U(kV)	Test voltage	Test current
$U \leqslant 75$	Maximum rated voltage	50% of maximum permissible current at test voltage for 0.1 s at the highest rotational speed for which the tube is rated
$75 \leqslant U \leqslant 150$	75 kV	
$U > 150$	50% of maximum rated voltage	

Tolerances

Nominal size of focal spot (mm)	% Tolerance[b] Minus	Plus
<0.8	0	50
0.8 through 1.5	0	40
>1.5	0	30

[a] National Electrical Manufacturers Association.
[b] In addition, for line focal spots only, a multiplication factor of 0.7 shall be applied to the dimension along the tube axis.

VII. Image Intensifiers

A. Definitions

1. Conversion factor (Gx)=ratio of the luminance of the output screen to the input exposure rate of applied x-radiation. The luminance is expressed in units of candela per square meter (cd/m^2) and the input exposure rate in milliroentgens per second (mR/s). Gx is expressed in units of cd·s/(mR·m^2). Gx is measured with 70±1 cm SID, an x-ray beam of 7±0.2 mm Al HVL, and an input screen exposure rate of 1±0.1 mR/s [20].

2. Contrast ratio=ratio between the luminance in the center of the output screen when the total entrance field is irradiated and the luminance of the output screen when a concentric circular area of 10% of the entrance field is completely shielded by a lead mask. The measurement is made at a peak potential of 50 kV and an input screen exposure rate of 1 mR/s.

3. Resolution=the greatest number of line pairs/mm visually resolved under optimal measuring conditions.

B. Typical image intensifier performance data[a]

Input screen diameter	Gx (cd·s/(mR·m^2))	Contrast ratio	Resolution (line pairs/mm)
23 cm (9 in)	70—200	10:1—20:1	2.5—5.4
15 cm (6 in)	40—200	10:1—20:1	3.0—6.0

[a] Based on information supplied by Philips, Picker, and Siemens Companies.

VIII. Computed Tomography

A. Mass densities, electron densities, effective atomic numbers, and measured Hounsfield numbers for several plastics and water[a] [21-23,25]

Materials	Density (g/cm^3)	Density ($electrons/cm^3$)	Effective atomic number Photoelectric	Coherent	Compton	Measured Hounsfield Numbers[b]
Water (H_2O) (22 °C)	0.998	3.33×10^{23}	7.52	7.04	5.21	(−0.4) 2.06
Polyethylene (C_2H_4) (low density)	0.92	3.16×10^{23}	5.54	5.11	3.79	(−103.6) −104.6
Polystyrene (C_8H_8)	1.05	3.40×10^{23}	5.75	5.50	4.61	(−28.2) −28.4
Nylon ($C_6H_{11}NO$)	1.15	3.79×10^{23}	6.22	5.80	4.57	(89.4) 88.6
Lexan ($C_{16}H_{14}O_3$)	1.20	3.81×10^{23}	6.41	6.05	5.21	(104.8) 102.8
Plexiglas ($C_5H_8O_2$)	1.19	3.87×10^{23}	6.57	6.16	4.97	(125.8) 121.2
Bakelite ($C_{43}H_{38}O_7$)	1.34	4.26×10^{23}	6.28	5.99	5.14	(263.6) 263.8
Teflon (C_2F_4)	2.20	6.36×10^{23}	8.48	8.32	8.13	(882)
Delrin (CH_2O)	1.42	4.55×10^{23}	7.04	6.66	5.50	(367.8)

[a] See also section IX of chapter one.
[b] Measured on an EMI scanner operating at a peak potential of 120 kV. Numbers in parentheses are from [23].

B. Mass densities, electron densities, effective atomic numbers, and measured Hounsfield numbers for selected human tissues[a] [21,24-26]

Materials	Density (g/cm^3)	Density ($electrons/cm^3$)	Effective atomic number Photoelectric	Coherent	Compton	Measured Hounsfield Numbers[b]
Adipose	0.916	3.08×10^{23}	6.37	5.78	4.33	−92
Blood	1.06	3.51×10^{23}	7.66	7.00	5.27	42 ± 18
Brain	1.03	3.44×10^{23}	7.68	6.95	5.11	35(30–40), gray matter
Heart	1.03	3.41×10^{23}	7.59	6.92	5.11	
Kidney	1.05	3.48×10^{23}	7.57	6.94	5.23	32 ± 10
Liver	1.08	3.59×10^{23}	7.66	6.92	5.16	60 ± 14
Muscle	1.06	3.51×10^{23}	7.67	7.01	5.29	44 ± 14
Pancreas	1.05	3.49×10^{23}	7.56	6.91	5.17	40 ± 14
Water (37 °C)	.99336	3.32×10^{23}	7.51	7.04	5.22	
Water (4 °C)	1.0000	3.34×10^{23}	7.51	7.04	5.22	

[a] See also section IX of chapter one.
[b] Measured on an EMI scanner operating at a peak potential of 120 kV.

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Notes

Notes

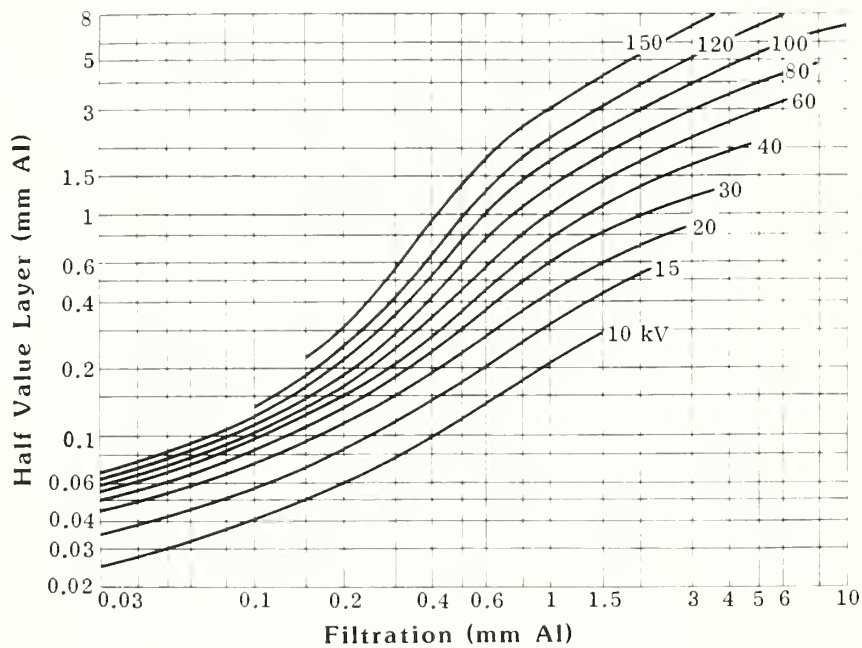
CHAPTER FOUR: RADIATION THERAPY

I. Teletherapy

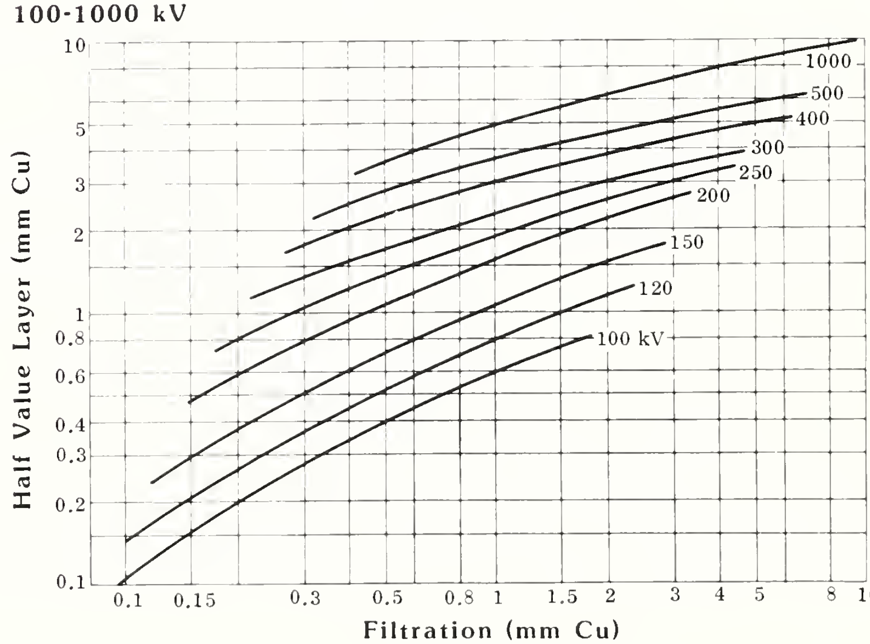
A. Photons

1. Relationship between tube voltage, filtration, and half-value layer (HVL) [1]

10-150 kV

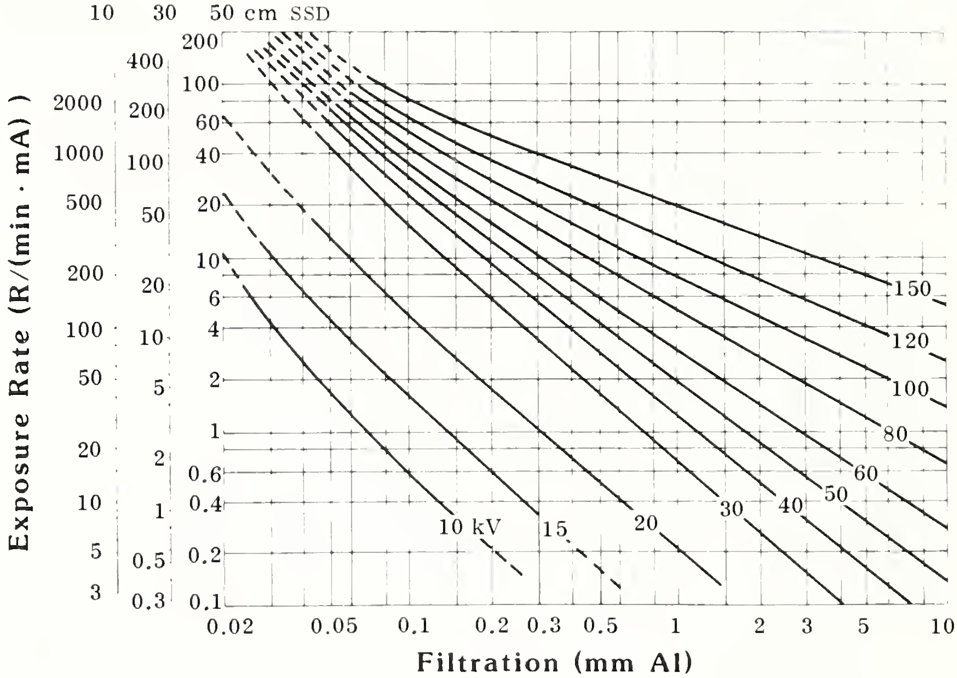


100-1000 kV

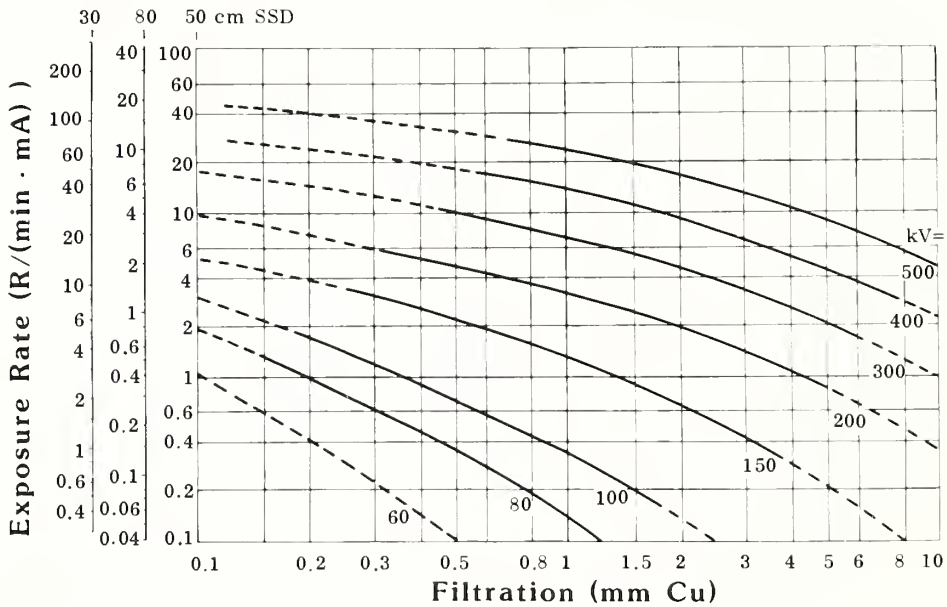


2. Exposure rate for different voltages and filtrations [1]

10-150 kV



60-500 kV



In half wave and fully rectified operation, the exposure rates on the same peak voltages are approximately half of the values given above. The average values given are for dc voltage and for an anode angle of 45° (therapy tubes). For voltages with greater fluctuation and for smaller anode angles (diagnostic tubes), the exposure rates are 20 to 40 percent lower.

Equivalent tube voltages[a]

kV	kV 1	kV 3
10	12	10.5
15	18	16
20	24	21
25	30	26
30	37	32
40	49	42
50	61	53
60	73	63
70	85	74
80	98	84
90	110	95
100	122	105
150	183	157
200	244	210
250	305	262
300	365	315
400	490	420
500	610	525
700	850	735
1000	1220	1050

[a] kV, constant dc voltage; kV 1, single phase; kV 3, three phase.

3. Absorbed dose at a point [2]

For x-rays generated at potentials above 150 kV and high energy γ rays, when a dosimeter is placed in a water phantom at a point such as D4 (see sec. A6), the *absorbed dose* is given by

$$D = R \cdot k_1 \cdot k_2 \cdot N \cdot F$$

where D is the absorbed dose at a point in the undisturbed water phantom (with the dosimeter absent) and R is the reading on the instrument. The meanings of the other symbols are as follows:

k_1 is a factor to correct for any difference in absolute temperature (T) and pressure (P) at the time of measurement, from those prevailing when the instrument was calibrated; (T_0,P_0).

$$k_1 = \left(\frac{P_0}{P}\right)\left(\frac{T}{T_0}\right)$$

k_2 is a factor to correct for differences, such as *quality,* between the radiation beam used for calibration and that prevailing at the point of measurement. An example would be to allow for the difference in both radiation quality and direction between exposure calibration in air and a measurement made at a point within an extended medium. For energies corresponding to ^{137}Cs gamma rays and above, k_2 is considered to be included in F.

N is the calibration factor, determined by the standardizing laboratory at a *stated quality* of radiation, and under stated conditions of temperature and pressure, for the conversion of the instrument reading into a statement of exposure, expressed in roentgens. In the low energy ranges N is obtained for each quality of radiation. For measurement of ^{137}Cs and ^{60}Co gamma rays and x-rays of higher energy, the calibration factor N is obtained with either ^{60}Co gamma rays or with x-rays generated at a potential of 2 MV.

F is a composite coefficient relating the exposure in roentgens to the absorbed dose in water expressed in rads. It is discussed in some detail in [16]. In the low energy range it is essentially the "f-factor" discussed in [17]. For measurement of ^{137}Cs and ^{60}Co gamma rays and x-rays of higher energy, it is identical with the factor known as C_λ discussed in [18]. Values for F are given in the following section. For measurements made directly within a patient, where this is possible, a slightly adjusted value of F should be used so that it refers to absorbed dose in the relevant tissue rather than water. Values of F applicable to muscle tissue are shown in the following section. They are obtained by multiplying F for water by a ratio of mass energy absorption coefficients $(\mu_{en}/\rho)_{tissue}/(\mu_{en}/\rho)_{water}$, averaged over the energy spectrum of the beam.

4. Absorbed dose to exposure ratios [2]

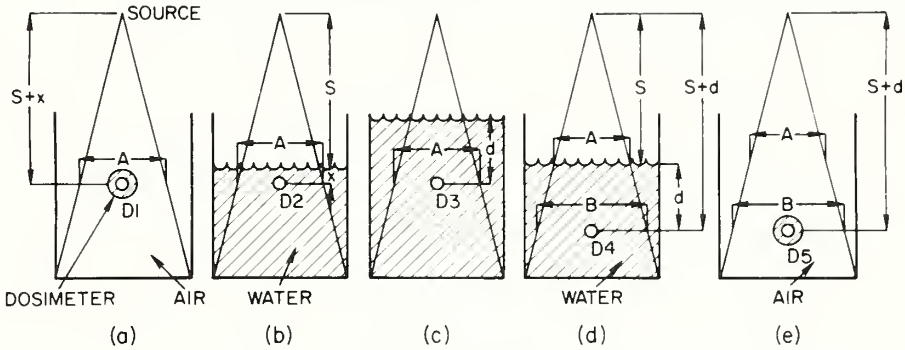
Radiation quality[a]	F(rad/R) for water	F(rad/R) for tissue	Radiation quality[a]	F(rad/R) for water	F(rad/R) for tissue
0.5 mm Al	0.89	.91	2 MV	0.95	.94
1 " "	0.88	.90	4 MV	0.94	.93
2 " "	0.87	.90	6 MV	0.94	.93
4 " "	0.87	.90	8 MV	0.93	.92
6 " "	0.88	.91	10 MV	0.93	.91
8 " "	0.89	.92	12 MV	0.92	.91
0.5 mm Cu	0.89	.92	14 MV	0.92	.91
1.0 " "	0.91	.93	16 MV	0.91	.90
1.5 " "	0.93	.95	18 MV	0.91	.90
2.0 " "	0.94	.95	20 MV	0.90	.89
3.0 " "	0.95	.95	25 MV	0.90	.89
4.0 " "	0.96	.96	30 MV	0.89	.87
^{137}Cs, ^{60}Co	0.95	.94	35 MV	0.88	.86

[a]Half-value layer, nuclide or generating potential in MV corresponding to maximum photon energy are stated to characterize the radiation quality.

5. Recommended phantom depths for absorbed dose calibrations [2]

Type of radiation	Depth (cm)
150 kV–10 MV x-rays	5
^{137}Cs and ^{60}Co γ rays	5
11 MV–25 MV x-rays	7
26 MV–50 MV x-rays	10

6. Operational definitions and relationships of Tissue-Air Ratio (TAR), Tissue-Maximum Ratio (TMR), Percentage Depth Dose (PDD), and the Backscatter Factor (BSF) [3]



The dosimeter with its equilibrium cap is positioned in air in the center of a field of size A. The dose is $D1$ (a). The tank is then filled to x, a level above the chamber just sufficient to obtain the maximum dose $D2$. x is the equilibrium depth (b). The tank is then filled to a depth d above the center of the chamber to obtain the dose $D3$(c). In all three cases, (a)–(c), the source-chamber distance, $S+x$, has not been changed. In (d), the water level is again set at S and the dosimeter is lowered to a depth d below the water surface to obtain the dose $D4$. The water is then removed and a final dose $D5$ is obtained (e). In all five cases, the field size A has not been changed.

The ratios of these doses define the following quantities:

$$D2 / D1 = \mathrm{BSF}\ (A) = \mathrm{TAR}\ (x, A)$$

$$D3 / D1 = \mathrm{TAR}\ (d, A)$$

$$D3 / D2 = \mathrm{TMR}\ (d, A)$$

$$D4 / D2 = \mathrm{PDD}\ (d, A, S)/100$$

$$D4 / D5 = \mathrm{TAR}\ (d, B)$$

where

TAR (x, A) is the tissue-air ratio at equilibrium depth x for a field of size A.

BSF (A) is the backscatter factor for a field of size A.

TAR (d, A) and TAR (d, B) are the tissue-air ratios at the depth d for fields of size A and B, respectively.

TMR (d, A) is the tissue-maximum ratio at depth d for a field of size A.

PDD (d, A, S) is the percentage depth dose at depth d for a field of size A at a source-surface distance of S.

The following relationships now follow:

$$\mathrm{TMR}\ (d, A) = \mathrm{TAR}\ (d, A) / \mathrm{BSF}\ (A)$$

$$\mathrm{TAR}\ (d, B) = (S + d / S + x)^2 \cdot (1/100) \cdot [\mathrm{BSF}\ (A)] \cdot [\mathrm{PDD}\ (d, A, S)]$$

$$\mathrm{TMR}\ (d, B) = (S + d / S + x)^2 \cdot (1/100) \cdot [\mathrm{PDD}\ (d, A, S)] \cdot [\mathrm{BSF}\ (A)/\mathrm{BSF}\ (B)].$$

The above equations define the relationship between the four basic depth dose quantities. Because of the scattering characteristic of high energy radiation, all four quantities depend upon the field size. Also, since radiation is rapidly attenuated in water, the TAR, TMR, and PDD decrease with increasing depth beyond x. Finally, since the PDD measurement involves moving the dosimeter, this quantity suffers the further restriction of being dependent upon the source-surface distance.

7. Measurement of teletherapy unit timer errors [4]

The single/multiple exposure method

This method was devised to give results of good statistical accuracy, unaffected by dosimeter linearity. n exposures of duration t/n are made, giving an integrated meter reading $R_{n(t/n)}$. The exposure rate E is then given by

$$E = \frac{R_t}{t+e} = \frac{R_{n(t/n)}}{t+ne} .$$

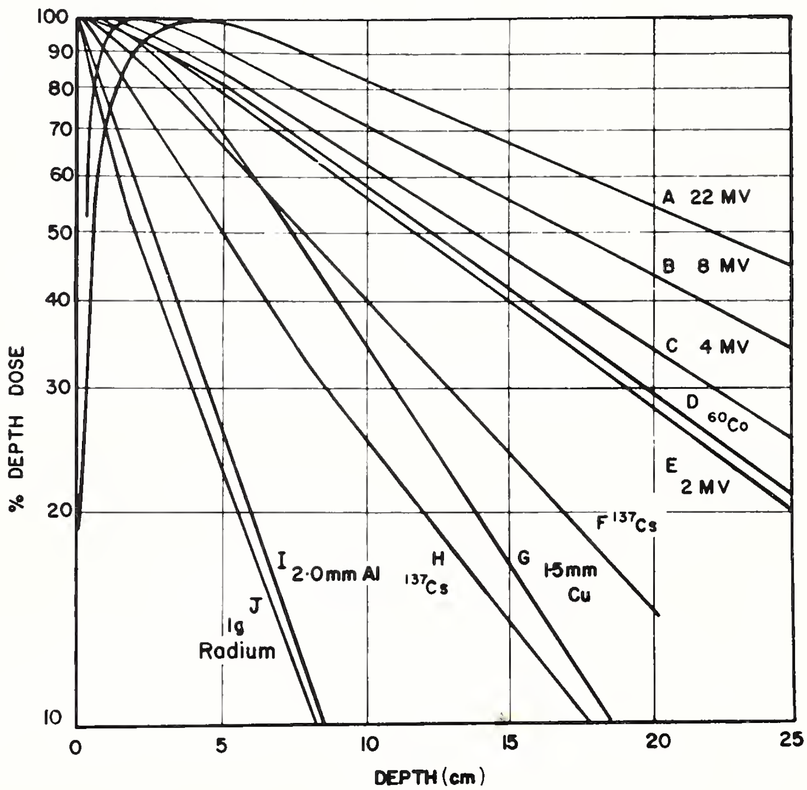
Hence

$$e = \left(\frac{R_{n(t/n)} - R_t}{nR_t - R_{n(t/n)}} \right) t,$$

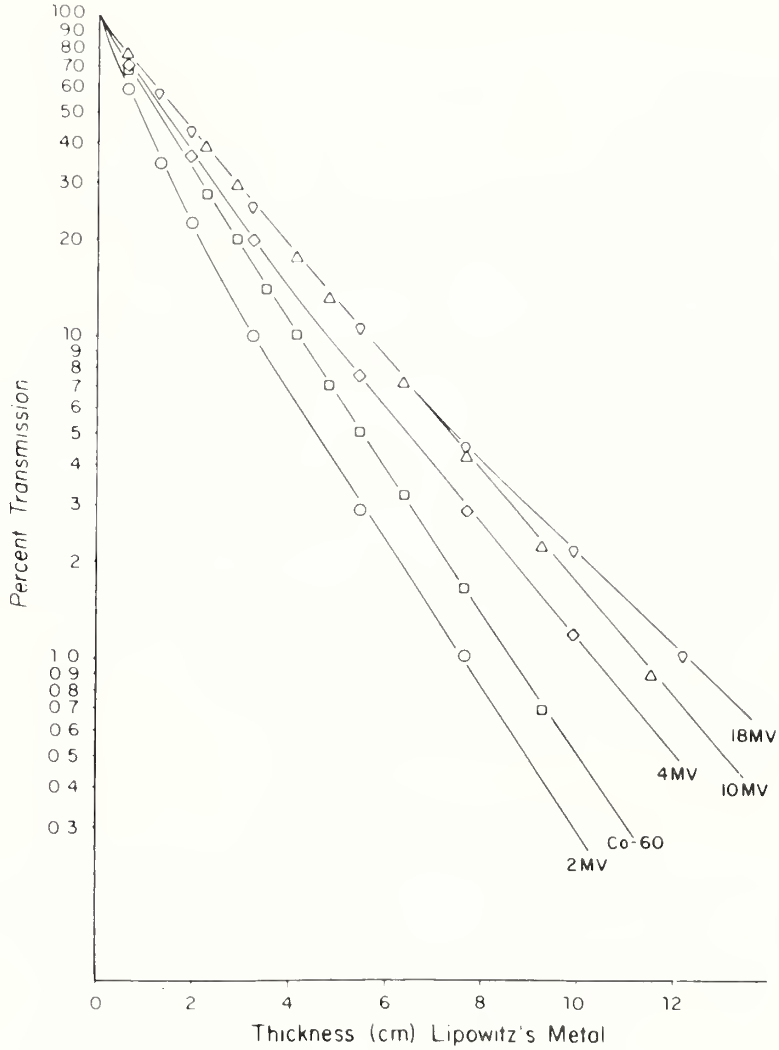
where R_t is the integrated meter reading for a single exposure of duration t.

8. Comparison of representative central axis depth doses (in water) [5]

A) 22 MV radiation with copper compensating filter, 10×10 cm field, SSD 70 cm. B) 8 MV radiation from linear accelerator, 10×10 cm field, SSD 100 cm. C) 4 MV radiation from linear accelerator, 10×10 cm field, SSD 100 cm. D) Cobalt 60, 10×10 cm field, SSD 80 cm. E) 2 MV Van de Graaf, 10×10 cm field, SSD 100 cm. F) Cesium 137, 10×10 cm field, SSD 35 cm. G) 200 kV, 10×10 cm field, HVL 1.5 mm Cu, SSD 50 cm. H) Cesium 137, 10 cm circle, SSD 15 cm. I) 120 kV, HVL 2.0 mm Al, Area 100 cm^2, SSD 15 cm. J) 1 g radium unit, 5 cm circle, SSD 5 cm.



9. Transmission and specifications of Lipowitz's metal [6,12]



Specifications

Melting temperature, °F	158
Weight, lb/in^3	0.339
Specific heat, liquid	0.040
Specific heat, solid	0.040
Latent heat of fusion, BTU/lb	14
Brinell hardness no.	9.2
Tensile strength, lb/in^2	5990
% elongation in slow loading	200
Composition, %:	
Bismuth	50.0
Lead	26.7
Tin	13.3
Cadmium	10.0

10. Side lengths of square fields equivalent to rectangular fields[a] (All dimensions are in centimeters) [2]

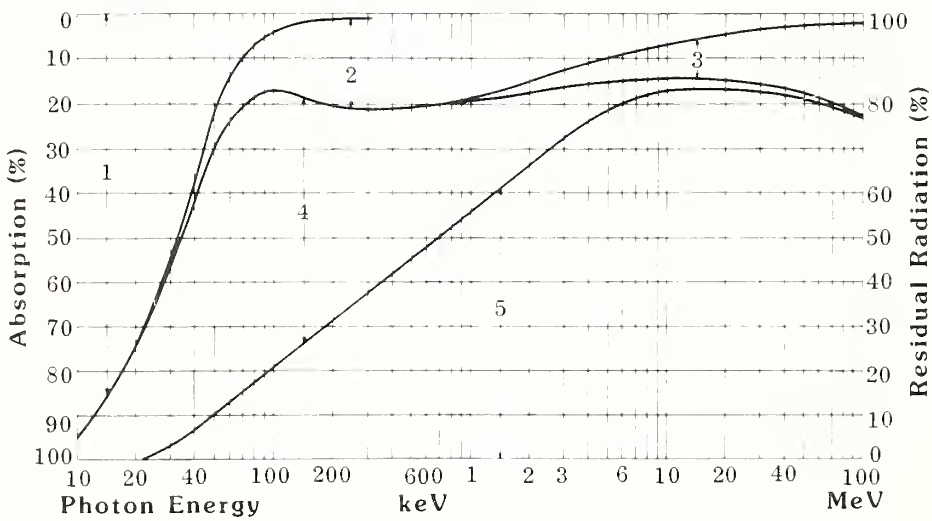
Long axis (cm)	Short axis (cm) 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	22	24	26	28	30
1	1.0																								
2	1.4	2.0																							
3	1.6	2.4	3.0																						
4	1.7	2.7	3.4	4.0																					
5	1.3	3.0	3.8	4.5	5.0																				
6	1.9	3.1	4.1	4.8	5.5	6.0																			
7	2.0	3.3	4.3	5.1	5.8	6.5	7.0																		
8	2.1	3.4	4.5	5.4	6.2	6.9	7.5	8.0																	
9	2.1	3.5	4.6	5.6	6.5	7.2	7.9	8.5	9.0																
10	2.2	3.6	4.8	5.8	6.7	7.5	8.2	8.9	9.5	10.0															
11	2.2	3.7	4.9	5.9	6.9	7.8	8.6	9.3	9.9	10.5	11.0														
12	2.2	3.7	5.0	6.1	7.1	8.0	8.8	9.6	10.3	10.9	11.5	12.0													
13	2.2	3.8	5.1	6.2	7.2	8.2	9.1	9.9	10.6	11.3	11.9	12.5	13.0												
14	2.3	3.8	5.1	6.3	7.4	8.4	9.3	10.1	10.9	11.6	12.3	12.9	13.5	14.0											
15	2.3	3.9	5.2	6.4	7.5	8.5	9.5	10.3	11.2	11.9	12.6	13.3	13.9	14.5	15.0										
16	2.3	3.9	5.2	6.5	7.6	8.6	9.6	10.5	11.4	12.2	13.0	13.7	14.3	14.9	15.5	16.0									
17	2.3	3.9	5.3	6.5	7.7	8.8	9.8	10.7	11.6	12.4	13.2	14.0	14.7	15.3	15.9	16.5	17.0								
18	2.3	4.0	5.3	6.6	7.8	8.9	9.9	10.8	11.8	12.7	13.5	14.3	15.0	15.7	16.3	16.9	17.5	18.0							
19	2.3	4.0	5.4	6.6	7.8	8.9	10.0	11.0	11.9	12.8	13.7	14.5	15.3	16.0	16.7	17.3	17.9	18.5	19.0						
20	2.3	4.0	5.4	6.7	7.9	9.0	10.1	11.1	12.1	13.0	13.9	14.7	15.5	16.3	17.0	17.7	18.3	18.9	19.5	20.0					
22	2.3	4.0	5.5	6.8	8.0	9.1	10.3	11.3	12.3	13.3	14.2	15.1	16.0	16.8	17.6	18.3	19.0	19.7	20.3	20.9	22.0				
24	2.4	4.1	5.5	6.8	8.1	9.2	10.4	11.5	12.5	13.5	14.5	15.1	16.3	17.2	18.0	18.8	19.6	20.3	21.0	21.7	22.9	24.0			
26	2.4	4.1	5.5	6.9	8.1	9.3	10.5	11.6	12.6	13.7	14.7	15.7	16.6	17.5	18.4	19.2	20.1	20.9	21.6	22.4	23.7	24.9	23.0		
28	2.4	4.1	5.6	6.9	8.2	9.4	10.5	11.7	12.8	13.8	14.8	15.9	16.8	17.8	18.7	19.6	20.5	21.3	22.1	22.9	24.4	25.7	27.0	28.0	
30	2.4	4.1	5.6	6.9	8.2	9.4	10.6	11.7	12.8	13.9	15.0	16.0	17.0	18.0	18.9	19.9	20.8	21.7	22.5	23.3	24.9	26.4	27.7	29.0	30.0

[a] An approximation to the side length L of an equivalent square can be obtained by the formula,

$$L = 2 \cdot W \cdot H / (W + H) \ ,$$

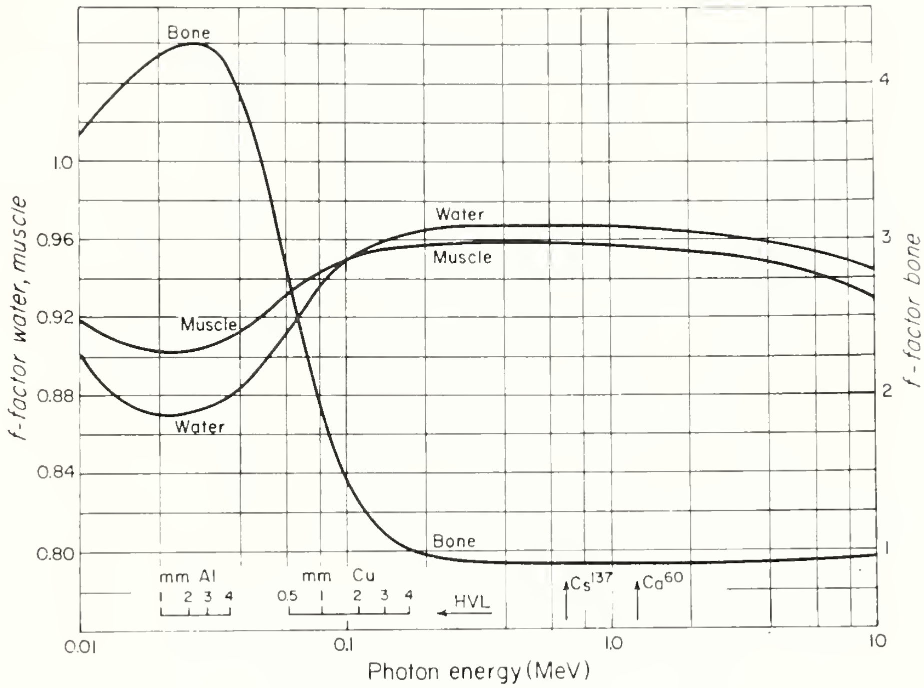
where W and H are the side lengths of the rectangular field.

11. Attenuation processes of x-rays in a 10-cm layer of water (100 cm² field size) [1]



1) Photoelectric absorption. 2) Compton absorption. 3) Pair production. 4) Scattering. 5) Transmitted primary radiation. For example: at 1 MeV, 18% of the photons undergo type 2 interaction, 25% undergo type 4, 57% are transmitted, and none undergo type 1 and 3.

12. **The *f*-factor as a function of photon energy for water, muscle, and bone [5] (see sec. XI, chapter one for definition of *f*)**



B. Electrons

1. Absorbed dose at a point in water [7]

For absorbed dose calibration, an ionization chamber calibrated for ^{60}Co γ-rays (or 2 MV x-rays) may be used.

$$D_w = RNC_E P_{wg}$$

where D_w is the dose in rads, R is the chamber reading (corrected for temperature, pressure, and saturation), N is the ^{60}Co calibration factor, and C_E is the dose conversion factor for electrons of energy E_z (MeV) at the depth z (cm) of the chamber. E_z is given by

$$E_z = E_0 \left[1 - \frac{z}{R_P}\right]$$

where E_0 (MeV) is the incident electron beam energy and R_P (cm) is the extrapolated practical range in water.

$$R_P = 0.521\ E_0 - 0.376$$

A good approximation to C_E is given by the empirical equation ($2 \text{ MeV} \leqslant E_z \leqslant 50 \text{ MeV}$)

$$C_E = 0.97\ E_z^{-0.048}.$$

The position of measurement will be displaced 0.75·r (r is the internal radius of the chamber in cm) toward the source of electrons from the center of a cylindrical ion chamber.

P_{wg} is the perturbation correction given by

$$P_{wg} = \frac{1}{1 + \frac{2}{5}\,\frac{br^{\frac{1}{2}}}{\pi}}$$

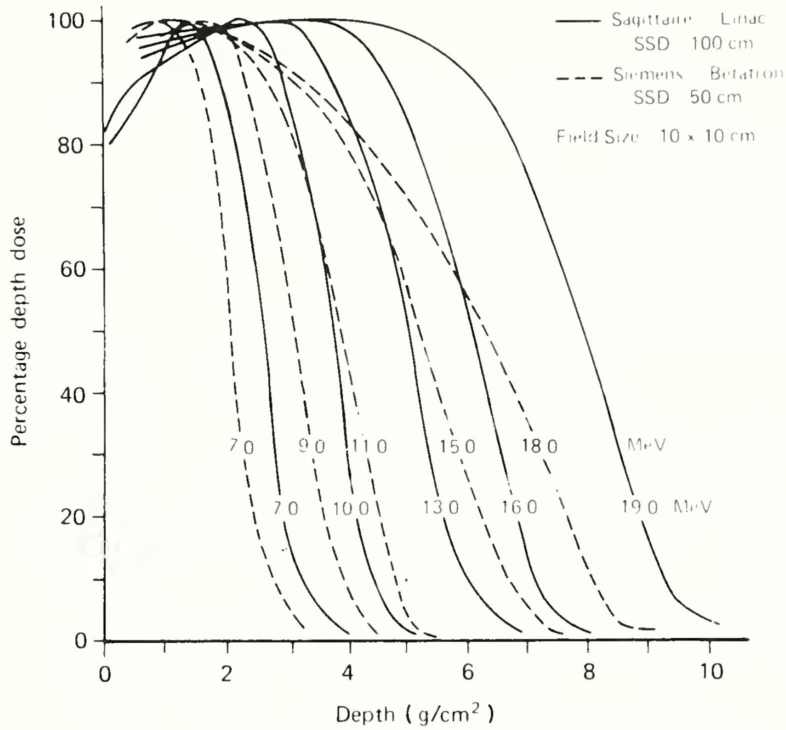
for a thimble ion chamber where

$$b = \frac{1.096(E_z + 0.511)}{E_z(E_z + 1.022)}\,.$$

2. Values of C_E for electron beams in water [13]

Depth in water z(cm)	Initial Electron Energy E_0 (MeV)									
	5	10	15	20	25	30	35	40	45	50
1	0.922	0.877	0.843	0.823	0.808	0.795	0.784	0.775	0.768	0.762
2		0.893	0.858	0.835	0.819	0.806	0.795	0.786	0.778	0.771
3		0.915	0.871	0.848	0.830	0.816	0.804	0.794	0.786	0.778
4		0.947	0.886	0.859	0.840	0.824	0.812	0.801	0.792	0.785
5		0.963	0.901	0.871	0.847	0.831	0.819	0.809	0.799	0.791
6			0.933	0.885	0.856	0.839	0.825	0.815	0.806	0.798
7			0.965	0.902	0.867	0.846	0.832	0.821	0.812	0.803
8				0.941	0.882	0.854	0.839	0.827	0.816	0.808
9				0.959	0.898	0.865	0.847	0.832	0.820	0.814
10				0.926	0.917	0.878	0.856	0.840	0.827	0.819
11					0.946	0.890	0.866	0.848	0.834	0.823
12					0.939	0.906	0.879	0.857	0.841	0.829
13						0.926	0.890	0.867	0.848	0.835
14						0.959	0.907	0.877	0.857	0.842
15						0.933	0.924	0.890	0.866	0.849
16							0.954	0.903	0.876	0.857
17							0.929	0.919	0.887	0.864
18								0.940	0.900	0.874
19								0.936	0.915	0.883
20									0.935	0.895
21									0.943	0.908
22									0.921	0.924
23										0.945
24										0.918

3. Comparison of representative central axis depth doses [7]



4. Thickness of Lipowitz's metal (mm) required to provide 90%, 93%, 95%, and 97% attenuation to the electron dose for various energies and field sizes [14]

Attenuation	Field size (cm×cm)	Electron energy (MeV)[a] 6 (6.5)	9 (9.4)	12 (12.8)	16 (16.5)	20 (20.5)
	4×4	1.8	3.2	4.9	6.8	9.5
90%	10×10	1.9	3.3	4.9	7.0	10.2
	25×25	1.9	3.4	5.0	7.7	12.5
	4×4	2.0	3.7	5.7	9.7	15.7
93%	10×10	2.1	3.8	5.8	10.2	18.0
	25×25	2.1	3.9	6.0	11.3	20.6
	4×4	2.2	4.3	7.3	16.0	23.5[b]
95%	10×10	2.3	4.4	8.5	18.0	25.0[b]
	25×25	2.3	4.7	10.0	20.0	
	4×4	2.5	5.5	17.0		
97%	10×10	2.8	7.5	19.0		
	25×25	2.8	8.0	20.0		

[a] The most probable energy of the incident electron beam as determined by range-energy measurements in a water phantom are given in parentheses directly below the nominal accelerator energies.
[b] Values obtained by linear extrapolation of the bremsstrahlung region.

II. Brachytherapy

A. Properties of selected radionuclides used in brachytherapy [10]

Property	^{222}Rn	^{226}Ra (both in equilibrium with decay products)	^{60}Co	^{125}I	^{137}Cs	^{182}Ta	^{192}Ir	^{198}Au
Half-life	3.823 days	1604 years	5.26 years	60.25 days	30.0 years	115.0 days	74.2 days	2.698 days
Gamma-ray energies (MeV)	0.047–2.44 Principal: 0.61, 0.77, 0.94 1.12, 1.24, 1.42, 1.77, 2.09		1.173, 1.332	0.0355	0.662	0.043–1.453 Principal: 0.100, 0.152, 0.156, 0.179, 0.222, 0.264, 1.12, 1.19, 1.22	0.136–1.062 Principal: 0.30, 0.31, 0.32, 0.47, 0.61	0.412–1.088 Principal: 0.412
Average γ-ray energy (MeV)	0.83		1.25	0.0284 (incl. x-rays)	0.662	0.67	0.38	0.416
Beta-ray spectra E_{max} (MeV)	0.017–3.26		0.313	None	0.514, 1.17	0.18–0.514	0.24–0.67	0.96
Other primary radiation	alpha	alpha		X-rays, 0.0272 0.0275, 0.0310 0.0318, MeV				
Specific γ-ray constant $(R \cdot cm^2 \cdot h^{-1} \cdot mCi^{-1})$	9.178[a] 8.35[c]	9.068[b] 8.25[c]	13.07	0.0423 0.052	3.226	7.692 6.8	4.89 4.57	2.327
Exposure rate constant $(R \cdot cm^2 \cdot h^{-1} \cdot mCi^{-1})$	10.27[a]	10.15[b]	13.07	1.089[d]	3.275	7.815	4.72	2.376
Rads/roentgen (muscle)	0.957		0.957	0.905	0.957	0.96	0.96	0.957
Rads/roentgen (compact bone)	0.921		0.923	4.2	0.924	0.92	0.93	0.929
HVL in water (cm) (narrow beam)	10.6		10.8	2.0	8.2	10	6.3	7.0
TVL in lead (cm) (broad beam)	4.2		4.6	~0.01	2.2	3.9	1.2	1.0

[a] No filtration; this value is obtained from the corresponding value for ^{226}Ra, since 0.988 mCi of ^{222}Rn is in equilibrium with 1 mg of ^{226}Ra.
[b] No filtration.
[c] 0.5 mm Pt filtration.
[d] From [19].

B. Linear source tables for radium

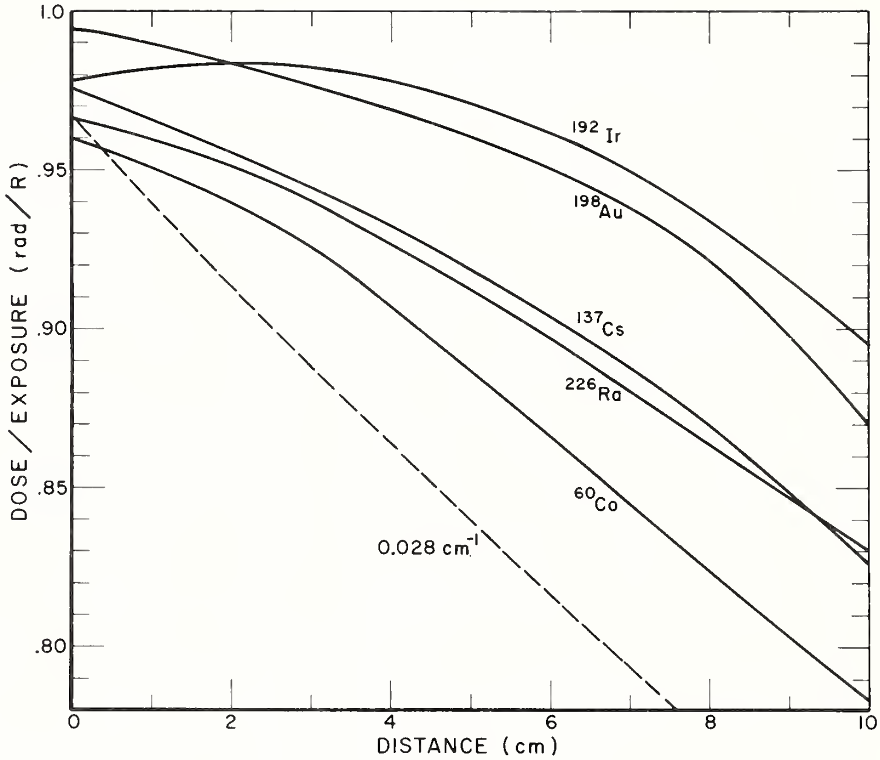
Rads per milligram-hour in tissue delivered at various distances by linear radium sources [8].

FILTRATION = 0.5 mm PLATINUM

(Dose rates are omitted where γ rays traverse more than 7 mm Pt)

Perpendicular Distance from Source (cm)	Distance Along Source Axis (cm from center)										
	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
	Active Length 1.5 cm										
0.25	50.67	43.75	11.94	3.34	1.48	.81	.50	—	—	—	—
0.5	20.26	16.95	8.18	3.38	1.70	1.00	.64	.44	.31	.23	.18
0.75	10.84	9.29	5.67	2.99	1.67	1.03	.69	.48	.35	.27	.21
1.0	6.67	5.89	4.10	2.52	1.55	1.01	.69	.50	.37	.28	.22
1.5	3.20	2.96	2.38	1.74	1.24	.89	.65	.48	.37	.29	.23
2.0	1.85	1.76	1.52	1.23	.96	.74	.57	.45	.35	.28	.23
2.5	1.20	1.15	1.04	.89	.74	.60	.49	.40	.32	.26	.22
3.0	.83	.81	.75	.67	.58	.49	.41	.34	.29	.24	.21
3.5	.61	.60	.57	.52	.46	.40	.35	.30	.26	.22	.19
4.0	.47	.46	.44	.41	.37	.33	.29	.26	.23	.20	.17
4.5	.37	.36	.35	.33	.30	.28	.25	.22	.20	.18	.16
5.0	.30	.29	.28	.27	.25	.23	.21	.19	.17	.16	.14
	Active Length 2.0 cm										
0.25	39.99	37.99	21.38	4.57	1.75	.90	.54	—	—	—	—
0.5	17.01	15.59	9.97	4.15	1.94	1.09	.68	.46	.33	.24	.18
0.75	9.56	8.71	6.14	3.38	1.85	1.11	.72	.50	.37	.27	.21
1.0	6.09	5.59	4.23	2.71	1.67	1.07	.72	.51	.38	.29	.23
1.5	3.04	2.85	2.37	1.79	1.29	.92	.67	.50	.38	.30	.24
2.0	1.79	1.71	1.51	1.24	.97	.75	.58	.45	.36	.29	.23
2.5	1.17	1.13	1.03	.89	.75	.61	.49	.40	.33	.27	.22
3.0	.82	.80	.75	.67	.58	.49	.42	.35	.29	.25	.21
3.5	.60	.59	.56	.51	.46	.40	.35	.30	.26	.22	.19
4.0	.46	.46	.44	.41	.37	.33	.29	.26	.23	.20	.17
4.5	.36	.36	.35	.33	.30	.28	.25	.22	.20	.18	.16
5.0	.29	.29	.28	.27	.25	.23	.21	.19	.17	.16	.14
	Active Length 5.0 cm										
0.25	17.29	17.25	—	—	—	—	—	—	—	—	—
0.5	8.21	8.17	8.02	7.66	6.73	4.31	1.88	.93	.55	—	—
0.75	5.15	5.11	4.97	4.66	4.00	2.80	1.59	.92	.58	.40	.29
1.0	3.62	3.58	3.45	3.20	2.74	2.04	1.33	.86	.57	.40	.30
1.5	2.10	2.07	1.98	1.82	1.58	1.27	.96	.70	.52	.39	.30
2.0	1.37	1.35	1.29	1.19	1.06	.89	.72	.57	.45	.35	.28
2.5	.96	.94	.91	.84	.76	.66	.56	.47	.38	.31	.26
3.0	.70	.69	.67	.63	.58	.51	.45	.38	.33	.27	.23
3.5	.54	.53	.51	.49	.45	.41	.36	.32	.28	.24	.21
4.0	.42	.42	.40	.38	.36	.33	.30	.27	.24	.21	.18
4.5	.34	.33	.32	.31	.29	.27	.25	.23	.21	.18	.16
5.0	.27	.27	.27	.26	.24	.23	.21	.20	.18	.16	.15

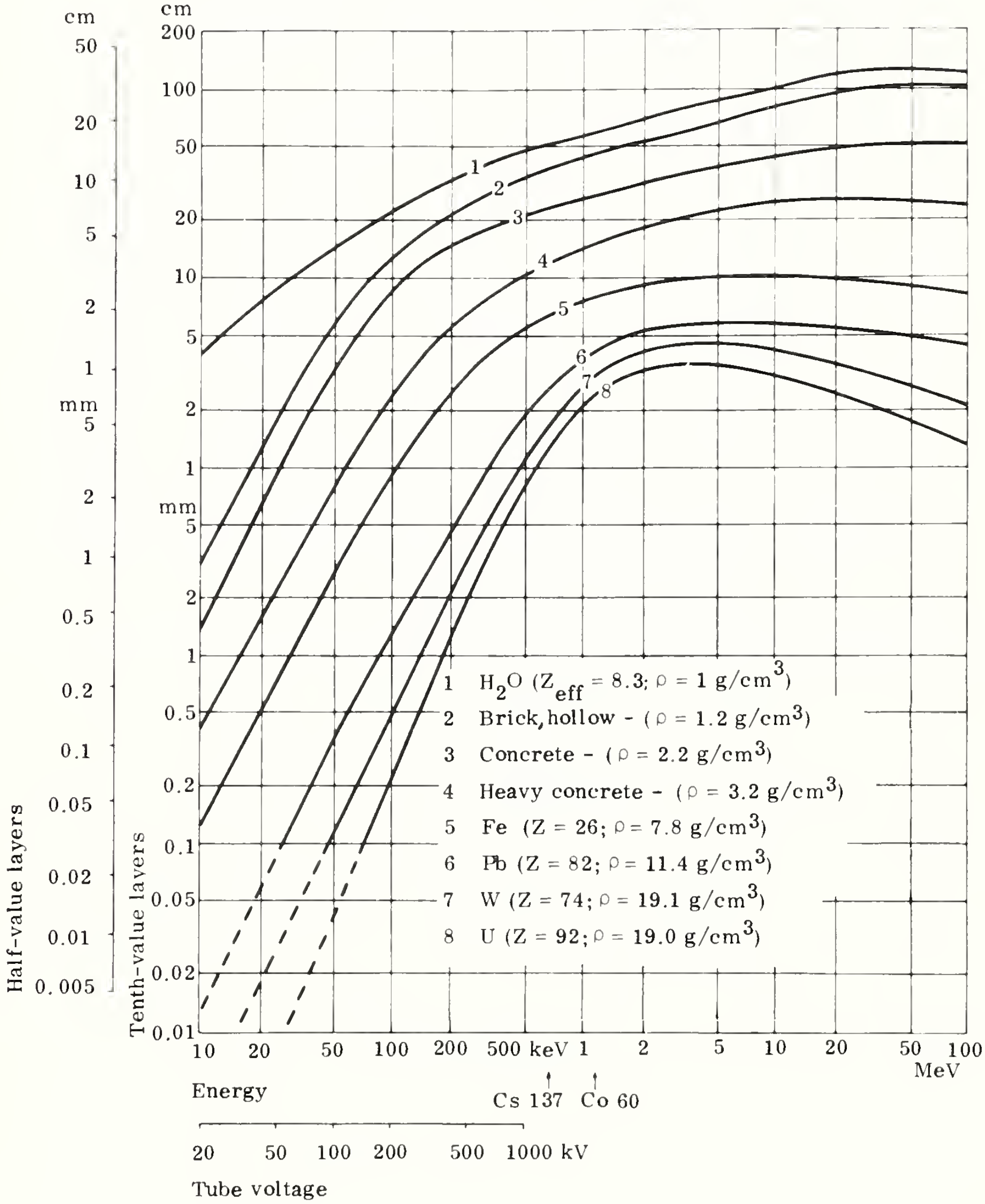
C. Dose/exposure curves in water [9]



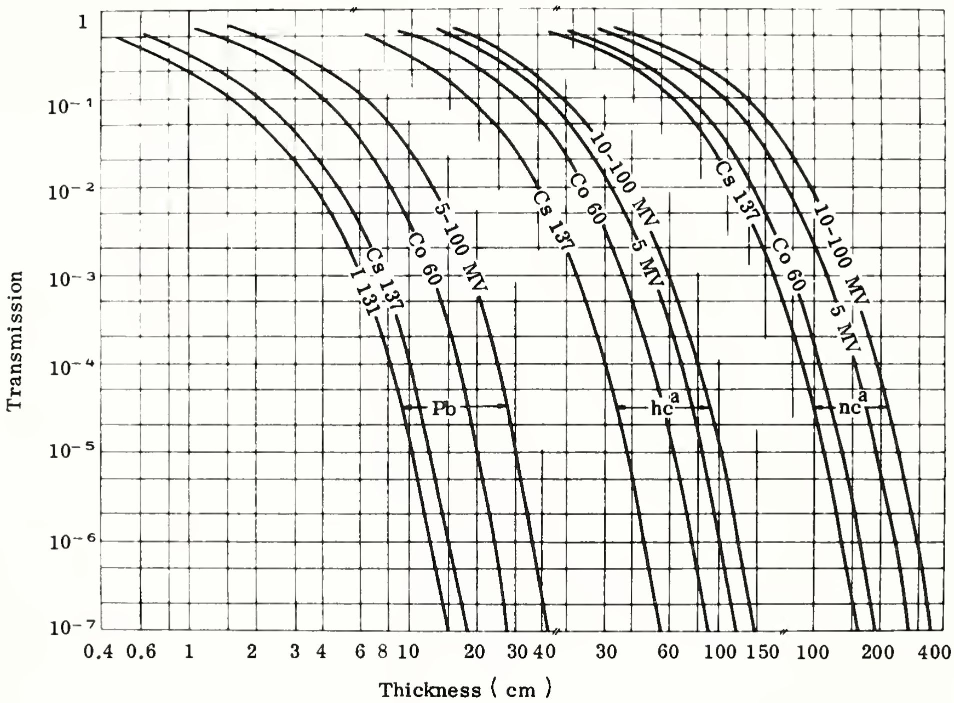
Dose per unit exposure vs distance for a point source of gamma radiation in water. The ordinates give the ratio of the absorbed dose to water at a given point, to the exposure in air at the same point in the absence of the water. The broken curve is calculated for exponential absorption with buildup, using the narrow-beam attenuation coefficient 0.028 cm^{-1}.

III. Protection and Miscellaneous Data

A. Average half-value and tenth-value layers of shielding materials (broad beams) [1]



B. Photon transmission factors through lead and concrete (^{131}I, ^{137}Cs, ^{60}Co, 5-100 MV) [1]



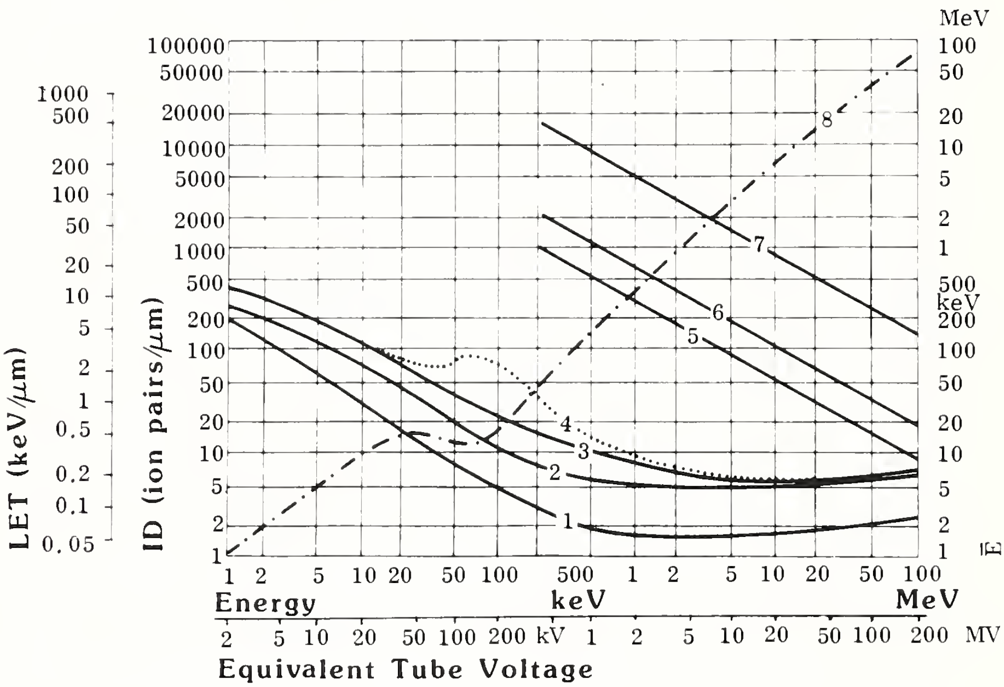
[a] hc—heavy concrete ($\rho = 3.2$ g/cm^3), nc—concrete ($\rho = 2.2$ g/cm^3).

C. Summary of measured fast-neutron fluences from electron accelerators [11]

Accelerator	Type of rad.	Energy (MeV)	Field (cm^2)	SSD (cm)	Target	Beam filter	Neutron fluence per rad of x rays or electrons (10^4 cm^{-2} rad^{-1}) (uncertainty): Inside field	Outside field (distance outside field edge)	
B.B.C. Betatron	x	32	10 × 10	80	...	...	0.51	0.18	(0.7 cm)
B.B.C. Betatron	x	33	25 × 25(?)	100	...	...	18 (30%-40%)	5.0 (±35%)	(27.5 cm)
	e	35	25 × 25(?)	110		...	0.66 (30%-40%)	0.29 (±35%)	(27.5 cm)
M.E.L. Linac	x	16	25 × 25(?)	100	...	...	15 (30%-40%)	7.1 (±35%)	(27.5 cm)
B.B.C. Betatron	x	32	10 × 10	100	...	...	130 (−)	85 (−)	(5 cm)
Siemens Betatron	x	19	7.6 × 11.4	50	...	...	73 (±15%)	17	(5 cm)
Sagittaire Linac	x	25	10 × 10	100	...	...	180 (±10%)	28	(5 cm)
Varian Clinac-18 Linac	x	10	10 × 10	100	6.3 mm Cu	W	1.06 (±20%)	1.52 (±20%)	(5 cm)
Allis Chalmers Betatron	x	25	10 × 10	100	1.6 mm Pt	Al	13.6 (±20%)	10.1 (±20%)	(5 cm)
B.B.C. Betatron	x	45	10 × 10	110	2.0 mm Pt	Pb	14.4 (±20%)	10.0 (±20%)	(5 cm)
Varian Clinac-18 Linac	x	10	25 × 25	100	Cu	W		0.4 (factor of ~2)	(100 cm)
Shimadzu Betatron	x	18	20 × 20	100	2 mm Pt	413 g Pb	4.8 (±50%)		
	x	23	20 × 20	100	2 mm Pt	413 g Pb	6.2 (±50%)	2.9 (±50%) 1.0 (±50%)	(5 cm) (20 cm)
	x	23	10 × 10	100	2 mm Pt	413 g Pb	6.0 (±50%)		
	e	25	14 × 14	105		0.3 mm Ta	0.05 (factor of ~2)		

D. Linear energy transfer (LET) and specific ionization density (ID) for different radiations in water (soft tissue) [1]

LET: energy transferred by an ionizing particle to matter along its path (expressed in keV/μm).
ID: specific ionization density of ionizing particles in matter expressed in ion pairs/μm.



1. LET and ID of primary electrons of specified energy.
2. LET and ID of electrons, including ionization due to secondary electrons.
3. LET and mean ID of electrons, integrated over the entire path length.
4. LET and mean ID of electrons released by x-rays of specified energy.
5. LET and ID of protons of specified energy.
6. LET and ID of deuterons of specified energy.
7. LET and ID of alpha particles of specified energy.
8. Mean energy of electrons released by monoenergetic x-rays in water ($\bar{E}$).

E. Properties of selected thermoluminescent materials [15]

Property/Type	LiF	$Li_2B_4O_7$:Mn	CaF_2:Mn [b]	CaF_2 (TLD-200) [b]	$CaSO_4$:Mn [b]	$CaSO_4$:Dy [b]
Density (g/cm^3) (Powder ∿ ½ of Solid)	2.64	∿2.4	3.18	3.18	2.61	2.61
Effective Atomic No (Z) for photoelectric absorption	8.2	7.4	16.3	16.3	15.3	15.5
Tl Emission Spectra	3500-6000Å (4000 max)	5300-6300Å (6050 max)	4400-6000Å (5000 max)	Peaks at 4835Å at 5765Å	4500-6000Å (5000 max)	4800Å; 5700Å
Temperature of main TL glow peak	195°C	200°C	260°C	180°C	110°C	220°C
Efficiency at ^{60}Co relative to LiF	1.0	0.15	10	30	70	20
Energy Response 30 Kev/^{60}Co	1.25	0.9	∿13	∿12.5	∿10	∿12.5
Useful Range	mR-3x10^5 R	50mR-10^6 + R	100μR-3x10^5 R	10μR-10^6 R	μR - 10^4 R	100μR - ∿10^5 R
Fading	Negligible [a] 5%/yr at 20°C	<5% in 3 months	10% in first 24 hours 15% total in 2 weeks	10% in first 24 hours [a] 16% total in 2 weeks	50% in first 24 hours	2% in 1 month 8% in 6 months
Physical Forms	TLD-100, 600, 700 Powder Ribbons Rods Bulbs Cards Cleaved Crystals	TLD-800 Powder Chips/Ribbons Bulbs Cards	TLD-400 on, Powder Chips/Ribbons Rods Bulbs	TLD-200 Powder Crystals Bulbs Cards	Powder	Powder

[a] Post-irradiation, pre-evaluation anneal for 10 minutes with LiF and 20 minutes with CaF_2 (TLD-200) at 100°C normalizes these materials and eliminates fading.

[b] The high sensitivity materials such as CaF_2 and $CaSO_4$ are extremely light (UV) sensitive, and fading is enhanced considerably. All of the high sensitivity materials should be handled, used and stored in opaque containers to prevent fading from light exposure.

Other TLD Materials include BeO:Mn, $CaSO_4$ (rare earth), Al_2O_3 (Mn), $CaSO_4$ (Tm), and Mg_2SiO_4 (Tb)

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Notes

Notes

CHAPTER FIVE: NON-IONIZING RADIATION

I. Ultrasonic Pressure Waves

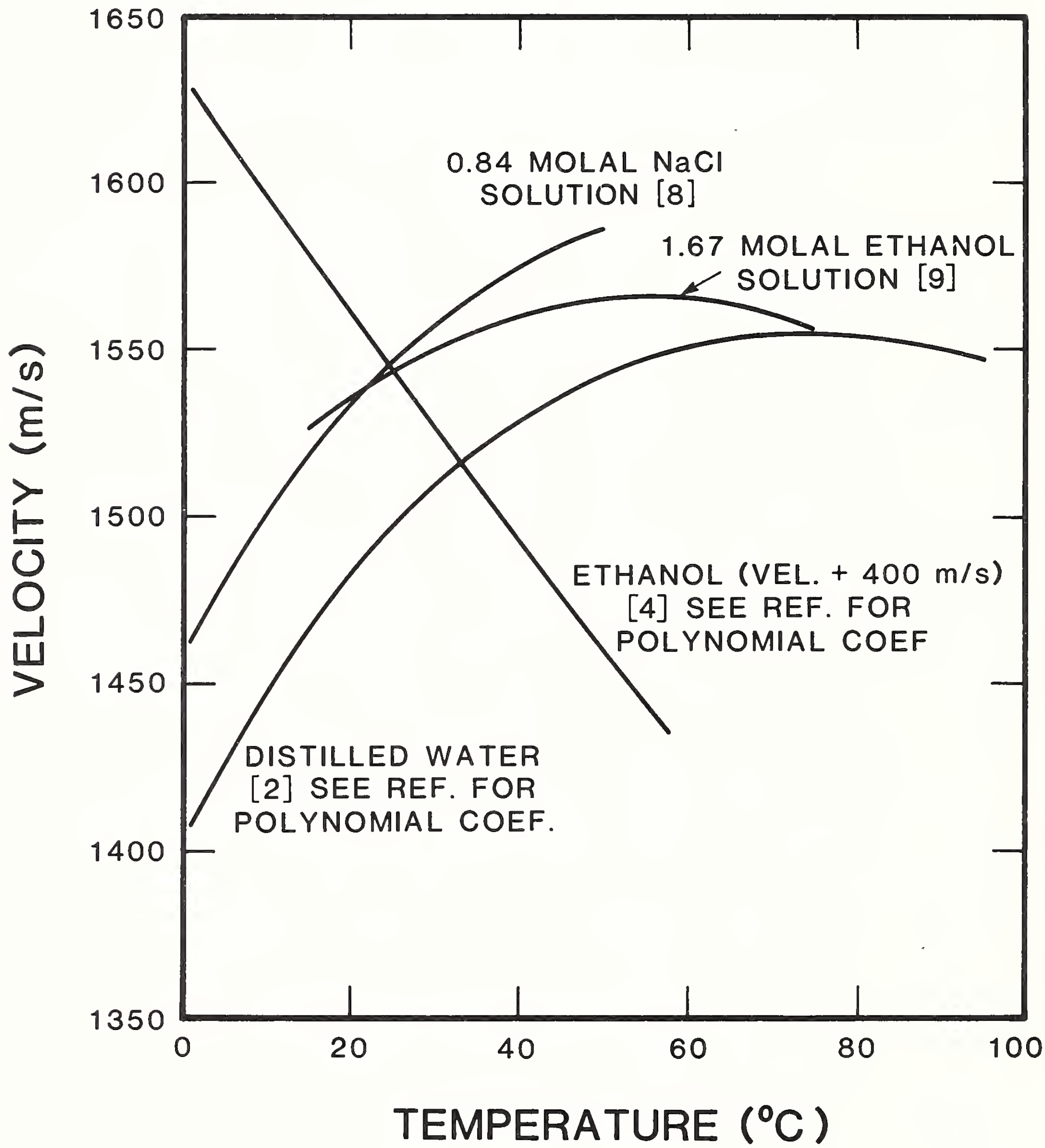
A. Acoustic properties of non-biologic materials

1. Table of density, acoustic velocity, and acoustic attenuation for non-biologic materials
(All values are for 20 °C and 1 atmosphere unless noted.)

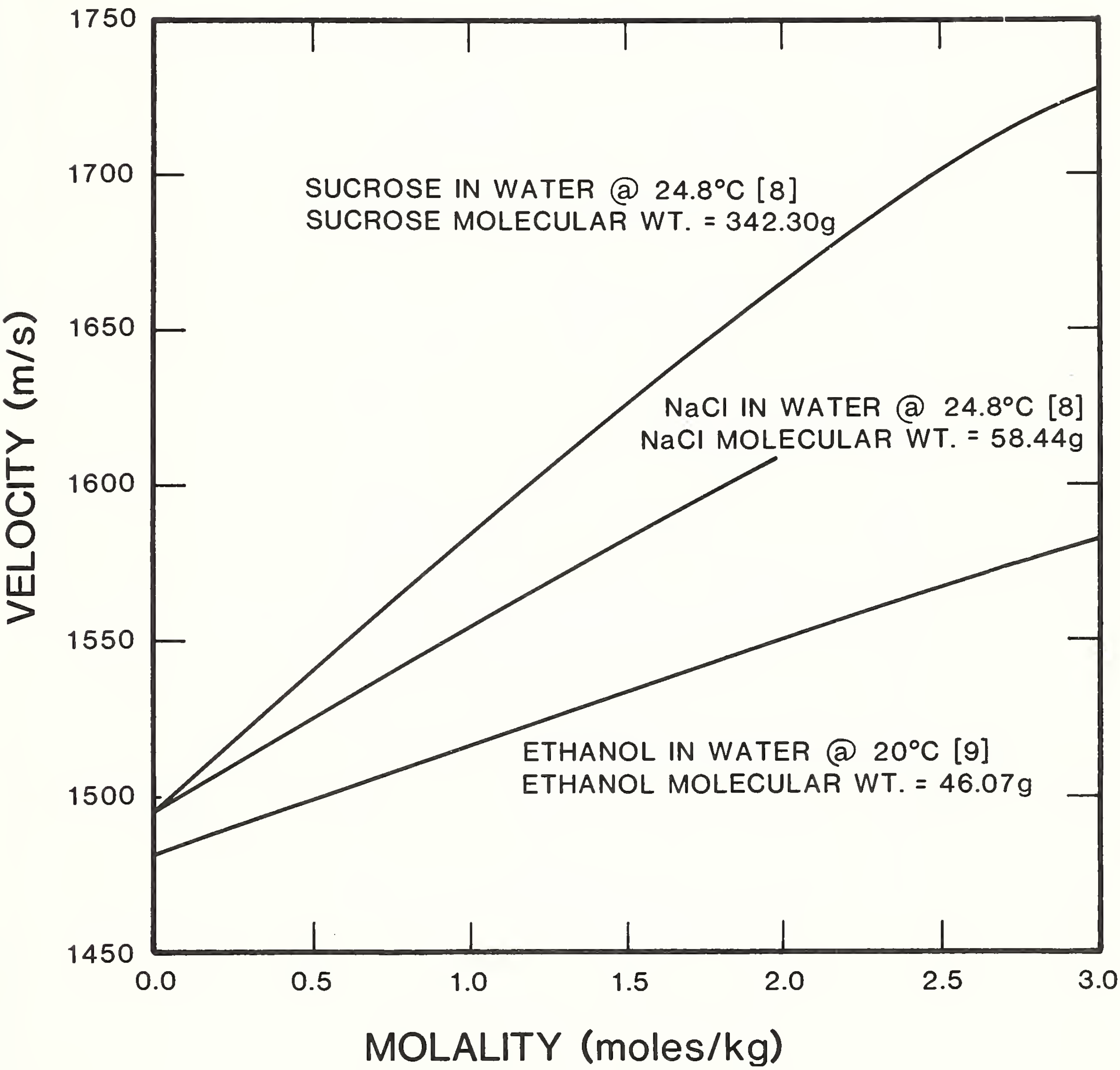
Material	Chemical formula	Density g/cm³	Velocity[a] $\frac{m}{s}$	Temperature coefficient of velocity $\frac{m/s}{°C}$	Attenuation coefficient at 1 MHz α, dB/cm	Approximate[b] frequency dependence of α	Reference den., vel., att.
Pure water[c]	H_2O	0.9982	1482.343(5)	+3.071	0.0022	f^2	1, 2, 3
Carbon tetrachloride	CCl_4	1.5896	939(10)	−2.7	.047 at 25 °C	f^2	1, 4, 3
Acetone	C_3H_6O	.7899	1196(10)	−4.5	.0047 at 30 °C	f^2	1, 4, 3
Ethanol, 95%	C_2H_6O, H_2O	.7998	1227(10)	−4.0			1, 4
Ethanol	C_2H_6O	.7893	1161.8	−3.5	.0042 at 30 °C	f^2	1, 3, 3
Methanol	CH_4O	.7914	1121.2	−3.3	.0026 at 30 °C	f^2	1, 3, 3
Glycerol	$C_3H_8O_3$	1.2613	1997	−2.2	.16 at 26 °C	f^2	1, 4, 5
Ethylene glycol	$C_2H_6O_2$	1.1088	1667	−2.2			1, 4
Castor oil	$C_{11}H_{10}O_{10}$	.969	1495	−3.6	.95 at ?	f^2	1, 1, 6
Aluminum	Al	2.695	6420		.018	f	3, 3, 6
Brass	.7Cu, .3Zn	8.6	4700		.02	f	3, 3
347 Stainless steel		7.91	5790				3, 3
Pyrex glass		2.32	5640				3, 3
Rubber gum		.95	1550				1, 1
Lucite		1.182	2680		2.0	f	3, 3, 6
Polyethylene		.90	1950	−8	4.7	$f^{1.1}$	3, 3 & 7, 6
Lexan polycarbonate		1.19	2280(.5)	−3.58			7, 7
Nylon		1.11	2620				3, 3

[a] The velocity is measured at the frequency noted in parentheses (MHz), however, for most materials little velocity dispersion is observed.
[b] Classical attenuation due to the effects of viscosity and heat conduction is observed in most liquids with a square dependence on frequency over a broad frequency range. Attenuation in solids is more complex. The frequency dependence noted is observed in the frequency range from 1 to 10 MHz.
[c] Doubly distilled water. The measured velocity is unaffected by dissolved gas.

2. Acoustic velocity vs temperature for water, ethanol, and sodium chloride solutions [2,4,8,9]



3. **Acoustic velocity vs concentration for solutions of sodium chloride, sucrose, and ethanol [8,9]**



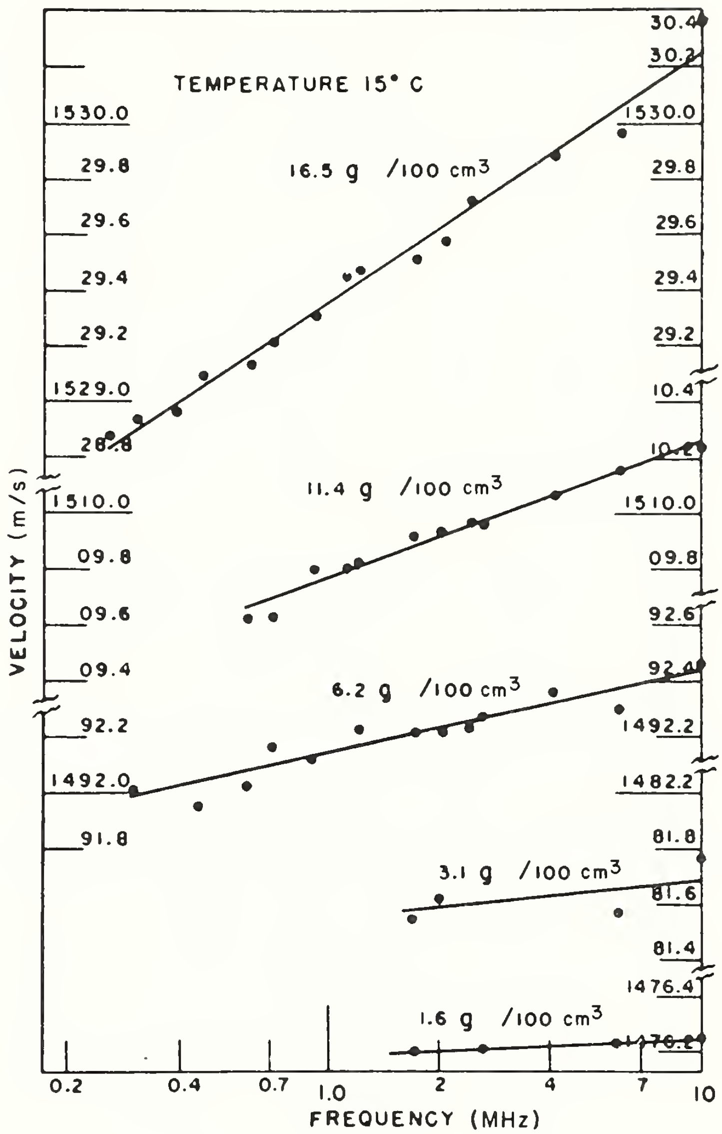
B. Acoustic properties of biologic materials

1. Table of acoustic velocity and attenuation for human tissues (all values are for fresh tissues, 37 °C) [10]

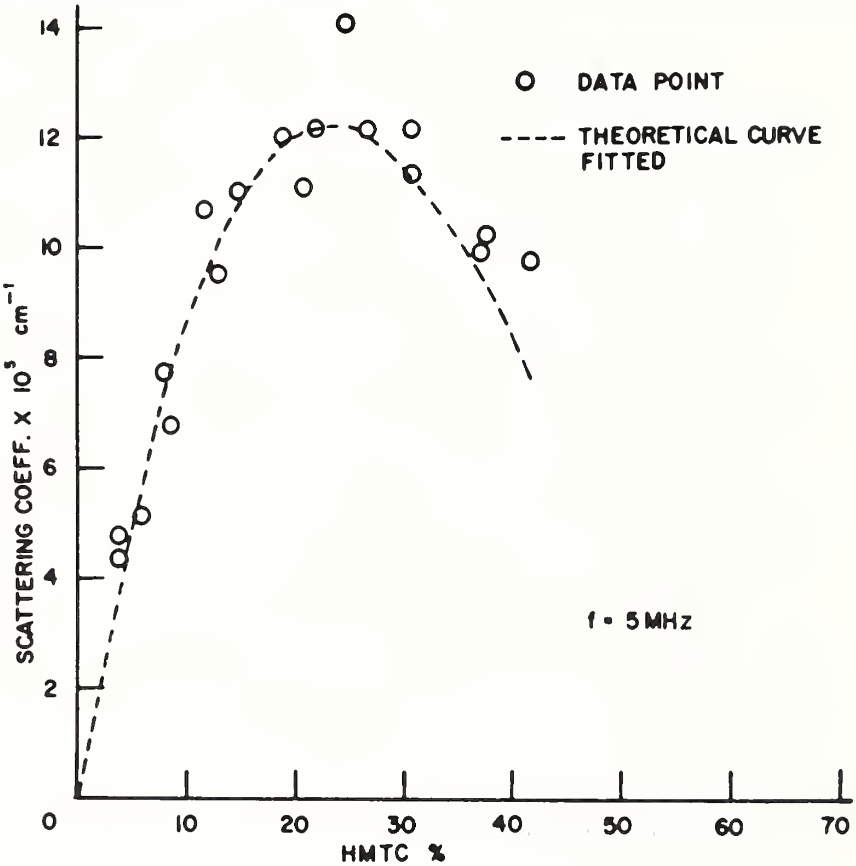
Tissue	Velocity (m/s)	Attenuation coefficient (α) at 1MHz (dB/cm)	Approximate frequency dependence of α
Amniotic fluid	1510±3	5.1×10^{-3}	1.6
Blood	1581 at 40% HMTC[a]	0.13	1.33
Brain, fetus	1520–1540	.63	1.27
Breast	1465±5 postmenopause 1529±5 premenopause		
Eye, lens	1638.4±3	.8	1.0
Eye, vitreous	1531.7±.9		
Fat	1479	.6	1.0
Liver	1540	.9	1.0
Muscle	1500–1610	1.3 for gastronemius muscle perpendicular to fibers	1.0

[a] Velocity in blood for a specified hematocrit (HMTC) = 1541.8 + (.98) (HMTC), (m/s).

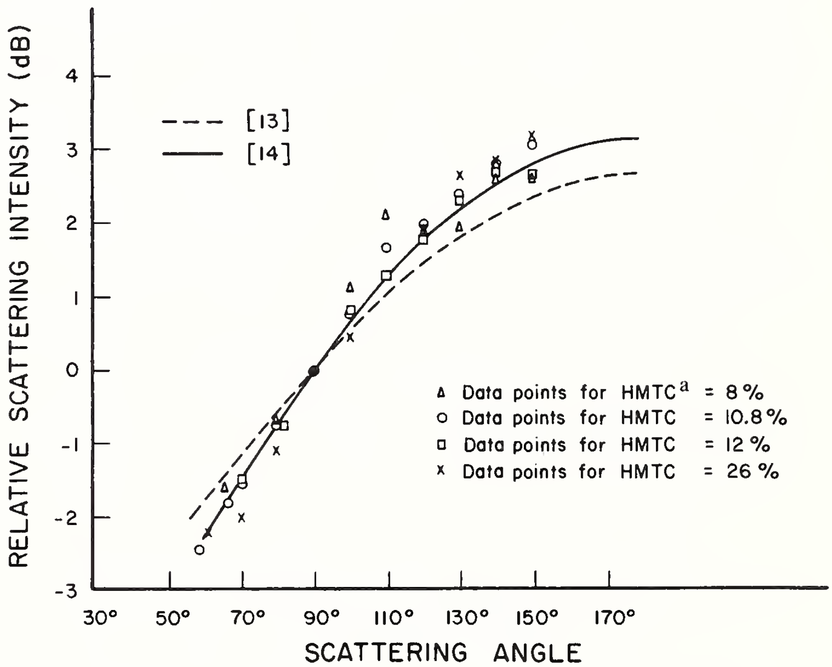
2. **Dispersion of the velocity of sound in solutions of human hemoglobin (15 °C) [11]**



3. **Volumetric scattering coefficient vs hematocrit (HMTC) for human blood at 5 MHz [12]**

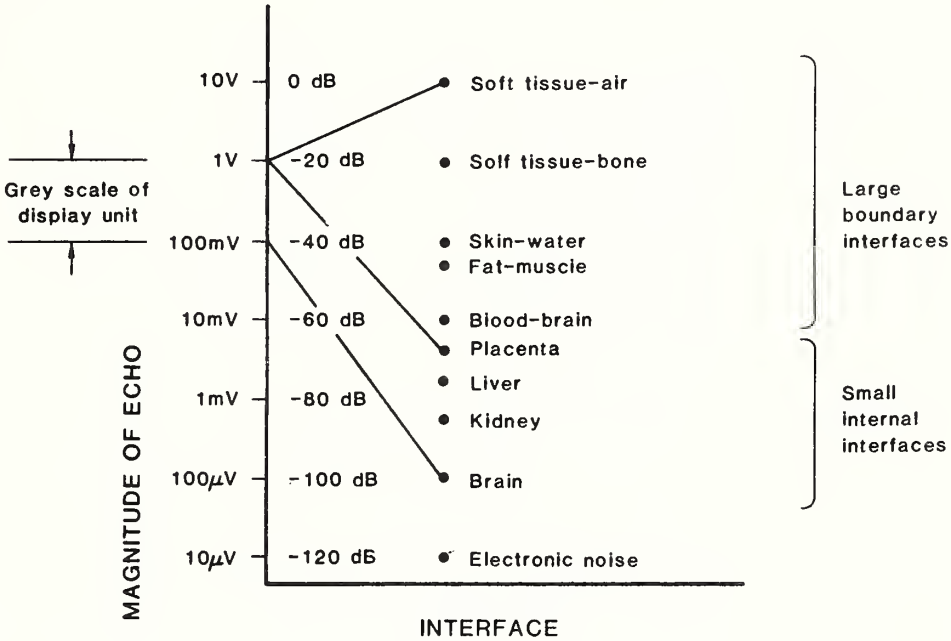


4. **Scattering intensity vs angle for human blood (normalized to 0 dB at 90 °F) [13,14]**



[a]HMTC-hematocrit.

5. The magnitude of ultrasonic pulse-echo reflections from biologic interfaces[a] [15]



[a] The basic principle of grey scale echography is illustrated by the diagonal lines, showing the compression of the internal echos into the major portion of the grey scale of the display unit.

C. Acoustic field data

1. Field parameters for a typical ultrasonic wave in biologic tissue [6]

Intensity, I	100 W/m^2
Frequency, f	3.5 MHz
Velocity, c	1540 m/s
Wavelength, λ	0.44 mm
Peak particle displacement, u_0	5.18 Angstroms
Peak particle velocity, v_0	1.13 cm/s
Peak particle pressure, p_0	0.17 atmosphere
Acoustic impedence, z	1.5×10^6 $kg/(m^2s)$
Radiation pressure (absorption)	0.66 mg/cm^2

Wavelength (λ): $\lambda = c/f$

c=propagation velocity, f=frequency

Particle displacement (u): $u = u_0 \sin(wt)$

$$w=2\pi f,\ u_0=\left[\frac{2I}{\rho c w^2}\right]^{1/2},\ \rho=\text{density}$$

Particle velocity (v): $v=v_0 \cos(wt)$ $v_0=u_0 w$

Intensity (I): $i=\rho c v_0^2/2$

Intensity level (dB): $\text{dB}=10 \log_{10} I/I_0$, $\text{dB}=20 \log_{10} A/A_0$

I_0=reference intensity
A_0=reference wave amplitude
$A_0 \propto$ pressure or transducer voltage

Particle pressure (p): $p=\rho c v$

Acoustic impedence (Z): $Z=\rho c=p/v$

Radiation pressure force (F):
F=W/c for a plane perfect absorber
F=2W/c for a plane perfect reflector
W=ultrasonic power, Watts

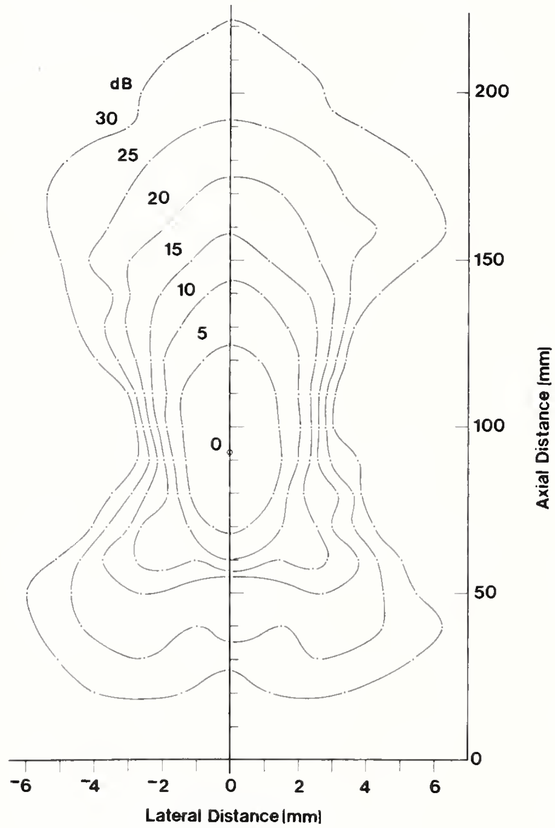
2. Acoustic power and intensity for diagnostic ultrasound instruments [16]

Transducer Code #, Nominal Frequency (MHz), Diameter (mm) Focal Length (cm)[a]	Ultrasound Unit and Pulse Repetition Rate (Hz)	Total Ultra-sonic Power Output (mW)	Average Intensity at Trans-ducer Face (W/m²)	Average Intensity at Focal Plane (W/m²)	Temporal Average, Spatial Peak In-tensity (W/m²)	Spatial Peak Intensity During the Pulse (W/m²)	Temporal and Spatial Peak Intensity (W/m²)
#1, 1, 13, 3.5	#1, 1538	4.6	35	46	68		2.6×10^4
#1, 1, 13, 3.5	#2, 1538	2.7	20				
#2, 1.6, 19, 8.8 F	#3, 806	9.1	32	280	360	3.9×10^5	2.7×10^6
#3, 1.6, 32, 10 F	#1, 1538	3.6	4.5				
#4, 2.0, 13, 5.5	#1, 1538	0.5	3.6	8.3	11.9	4.9×10^3	1.9×10^4
#5, 2.0, 13, 5.5	#4, 520	4.2	32				
#6, 2.0, 13, 5.5	#4, 520	2.8	21				
#7, 2.2, 13, 6.3	#5, 676	5.8	44				
#8, 2.2, 13, 6.3	#5, 676	9.4	71				
#9, 2.25, 13, 6.2	#6, (Power 1)	1.04	7.8				
#9, 2.25, 13, 6.2	#6, (Power 2)	5.1	38	(88)	(126)	(8.0×10^4)	(3.1×10^5)
#9, 2.25, 13, 6.2	#6, (Power 3)	6.4	48	(110)	(159)	(1.0×10^5)	(3.9×10^5)
#10, 2.25, 13, 6.7	#1, 1538	4.4	33	58	96		8.6×10^4
#10, 2.25, 13, 6.7	#2, 1538	5.3	40				
#11, 2.25, 13, 6	#7, 1000	1.52	11.4		34		1.2×10^5
#12, 2.25, 13, 6, F	#7, 1000	2.9	22				
#13, 2.25, 13, 7, F	#3, 806	5.6	42				
#14, 2.25, 19, 8.5, F	#3, 806	6.8	24	470	660	5.0×10^5	4.8×10^6
#15, 2.25, 19, 9, F	#6, (Power 1)	0.83	2.9	(57)	(80)	(5.2×10^4)	(5.0×10^5)
#15, 2.25, 19, 9, F	#6, (Power 2)	6.3	22	(430)	(610)	(4.0×10^5)	(3.8×10^6)
#15, 2.25, 19, 9, F	#6, (Power 3)	11.4	40	(780)	(1100)	(7.1×10^5)	(6.9×10^6)
#16, 2.25, 19, 8.4, F	#8, 1000	14.4	51		1690	1.6×10^6	1.7×10^7
#17, 2.3, 25, 10, F	#1, 1538	2.9	5.7				
#18, 3.5, 13, 10	#7, 1000	2.2	17				
#19, 3.5, 13, 7.4, F	#1, 1538	1.12	8.4	81	110		2.5×10^5
#19, 3.5, 13, 7.4, F	#2, 1538	1.87	14				
#20, 3.5, 13, 5, F	#7, 1000	1.57	11.8	59	62		3.4×10^5
#21, 3.5, 19, 8.4, F	#8, 1000	10.1	36	920	1220	2.0×10^6	1.5×10^7
#21, 3.5, 19, 8.4, F	#1, 1538	2.4	8.5	280	380	1.5×10^5	1.1×10^6
#22, 3.5, 19, 7.5, F	#3, 806	2.7	9.5	390	580	5.9×10^5	3.7×10^6
#23, 5.0, 6, 5, F	#8, 1000	1.9	60				
#24, 5, 10, 8.3	#1, 1538	1.4	18				
#24, 5, 10, 8.1	#2, 1538	2.6	20				
#25, 5.0, 13, 7	#3, 806	1.48	11.1				
#26, 5.0, 13, 7	#3, 806	1.62	12.2				
#27, 5, 19, 6, F	#1, 1538	0.50	1.7	250	350		1.4×10^6
#28, 2.0, 10 x 10, 6.5	#9, 2600				0.58		8.9×10^3
#29, 2.0, 10 x 10, 6.0	#10, 2600				0.14		4.0×10^3

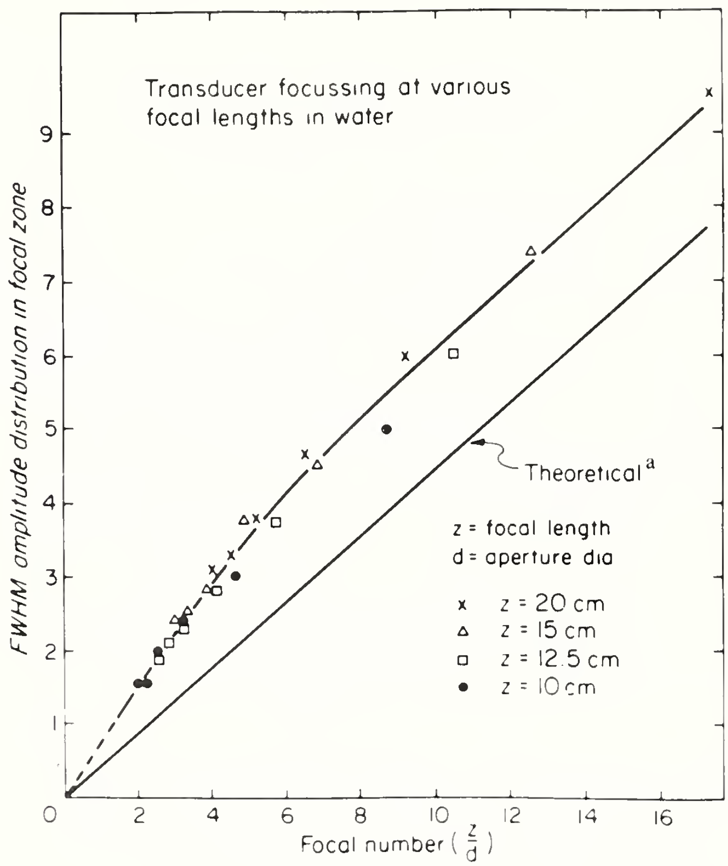
[a] When F appears to the right of the focal length value, the transducer is focused. Otherwise the transducer is unfocused (flat) and the focal length is interpreted as the near field length.

3. **The spatial distribution of acoustic intensity for a narrow-band focused transducer (experimental) [17]**

Diameter = 15 mm.
Focal length = 100 mm.
Frequency = 2.25 MHz, CW.



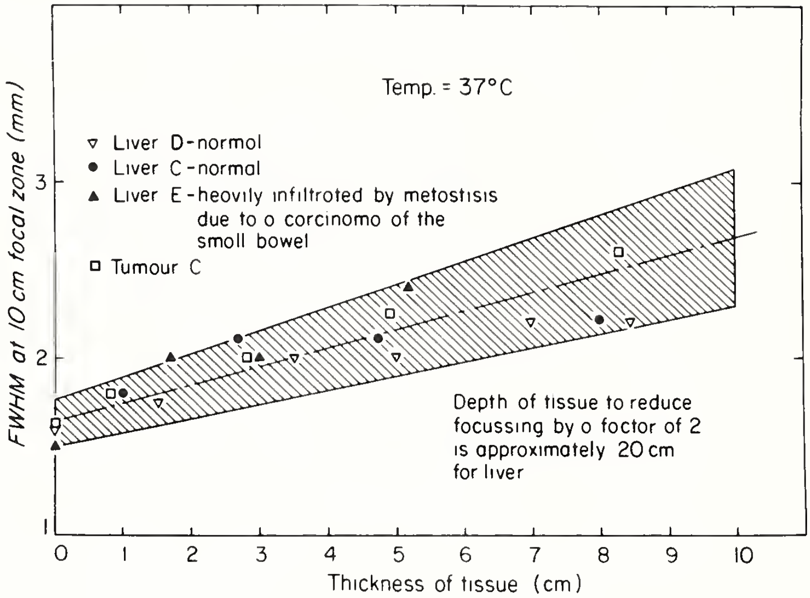
4. Acoustic field focal zone widths for 5 MHz focused transducers as a function of focal length and diameter [18]



[a]Calculated using the Fraunhofer approximation and for continuous waves (narrow-band).

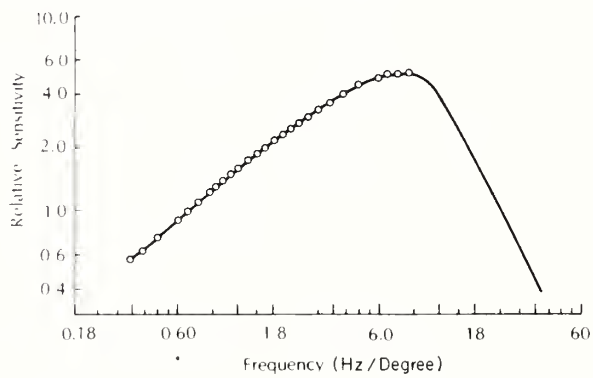
5. **Acoustic field focal zone width after penetration through varying thicknesses of human tissue [18]**

Frequency = 5 MHz.
Focal length = 100 mm.
Diameter = 50 mm.



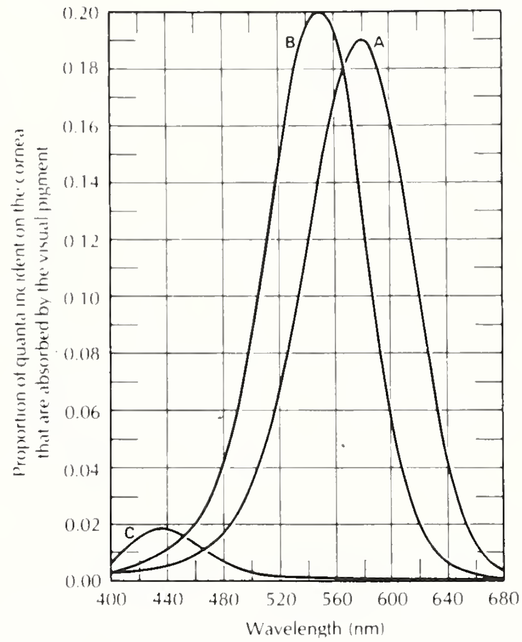
II. Visible Electromagnetic Radiation (4–8 × 10^{14} Hz)

A. Human visual modulation transfer function [19]

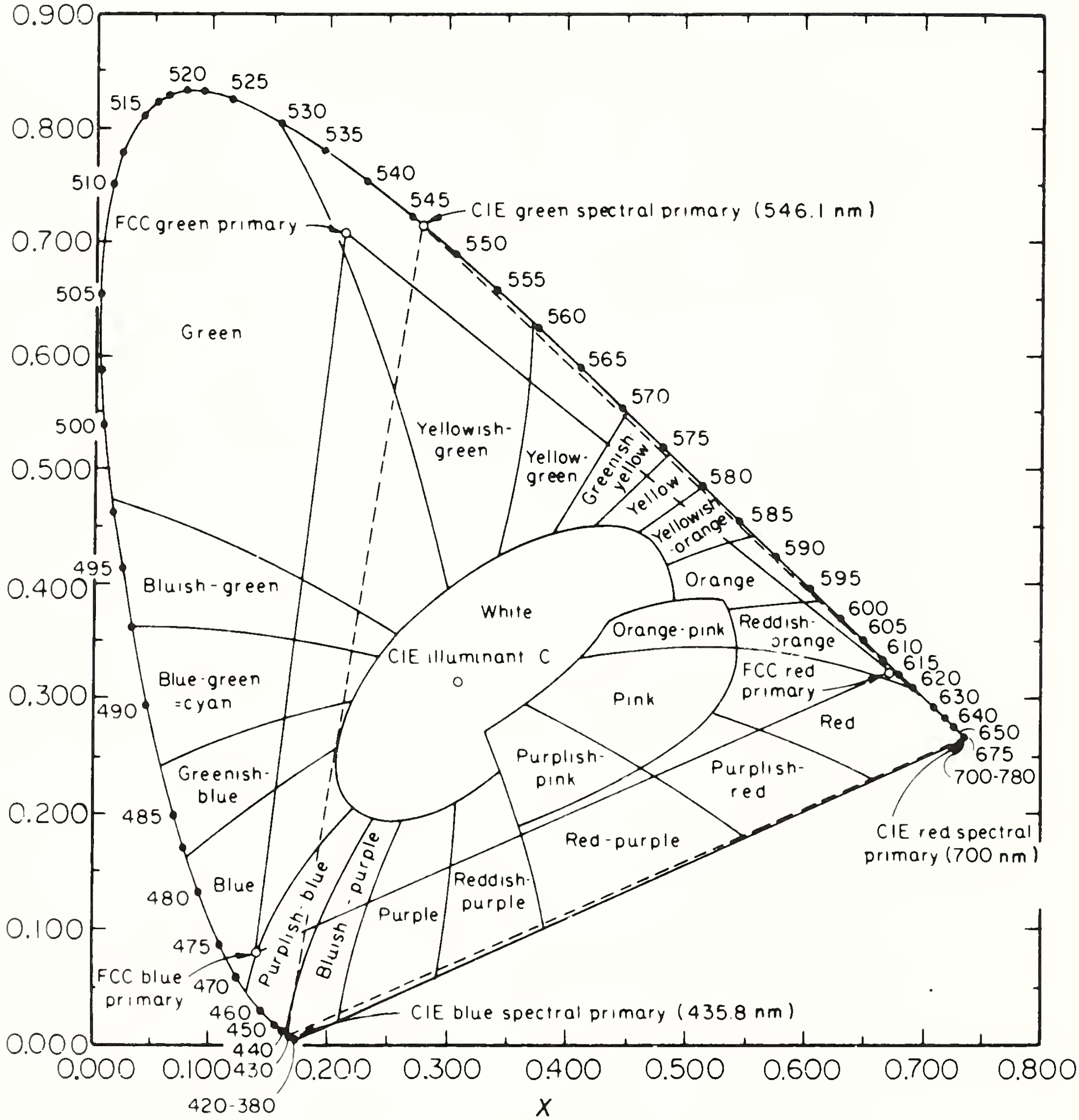


The data points are the results of a contrast matching experiment. The region without data points is an estimate of the high frequency portion of the curve based upon threshold measurements.

B. **Absorption spectra of the three color-systems in a human eye with normal color vision. (A, B, and C refer, respectively, to the three image receptors usually associated with red, green, and blue response) [19]**

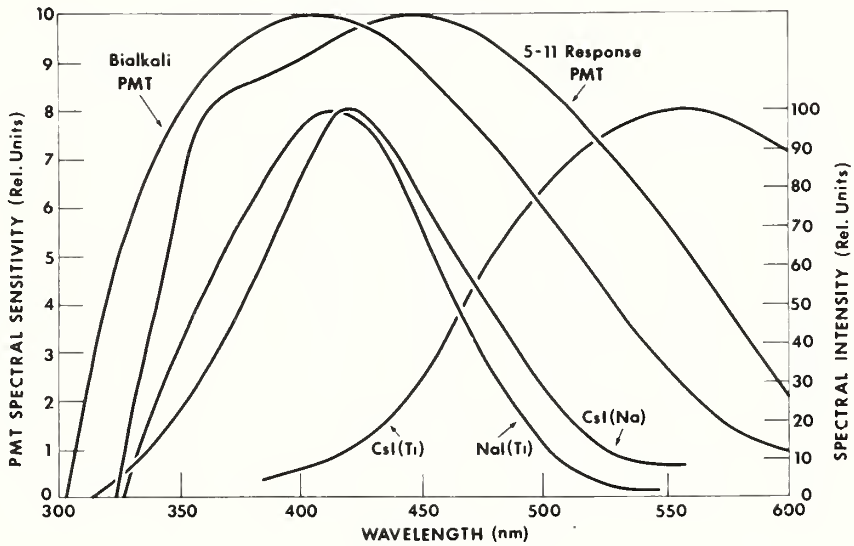


C. The CIE chromaticity diagram [20]



The CIE (Comité International d'Eclairage) diagram is the worldwide standard method of representing color. The x and y coordinates are transformations of three color primaries defined by CIE. The chromaticity diagram displays the hue and saturation of colors. The hue varies on the diagram with the angle measured with the white point (illuminant C) as the vertex. Saturation is measured by the radial distance from the white point at the center of the chart.

D. Emission spectra of NaI and CsI scintillation crystals and spectral sensitivities of S-11 and bialkali photomultiplier tubes [21]



III. Electromagnetic Radiation: Radiofrequency (10^4—10^{10} Hz); Microwave (10^9—10^{12} Hz)

A. Properties of electromagnetic waves in muscle, skin, and tissues with high water content, from 1 MHz to 10 GHz [22]

		Muscle, Skin, and Tissues with High Water Content				Reflection Coefficient			
						Air–Muscle Interface		Muscle–Fat Interface	
Frequency (MHz)	Wavelength in Air (cm)	Dielectric Constant	Conductivity (mho/m)	Wavelength (cm)	Depth of Penetration[a] (cm)	magnitude	phase shift	magnitude	phase shift
1	30000	2000	0.400	436	91.3	0.982	+179		
10	3000	160	0.625	118	21.6	0.956	+178		
27.12	1106	113	0.612	68.1	14.3	0.925	+177	0.651	−11.13
40.68	738	97.3	0.693	51.3	11.2	0.913	+176	0.652	−10.21
100	300	71.7	0.889	27	6.66	0.881	+175	0.650	−7.96
200	150	56.5	1.28	16.6	4.79	0.844	+175	0.612	−8.06
300	100	54	1.37	11.9	3.89	0.825	+175	0.592	−8.14
433	69.3	53	1.43	8.76	3.57	0.803	+175	0.562	−7.06
750	40	52	1.54	5.34	3.18	0.779	+176	0.532	−5.69
915	32.8	51	1.60	4.46	3.04	0.772	+177	0.519	−4.32
1500	20	49	1.77	2.81	2.42	0.761	+177	0.506	−3.66
2450	12.2	47	2.21	1.76	1.70	0.754	+177	0.500	−3.88
3000	10	46	2.26	1.45	1.61	0.751	+178	0.495	−3.20
5000	6	44	3.92	0.89	0.788	0.749	+177	0.502	−4.95
5800	5.17	43.3	4.73	0.775	0.720	0.746	+177	0.502	−4.29
8000	3.75	40	7.65	0.578	0.413	0.744	+176	0.513	−6.65
10000	3	39.9	10.3	0.464	0.343	0.743	+176	0.518	−5.95

[a] Depth for attenuation by 1/e.

B. Properties of electromagnetic waves in fat, bone, and tissues with low water content, from 1 MHz to 10 GHz [22]

		Fat, Bone, and Tissues with Low Water Content							
						Reflection Coefficient			
						Air–Fat Interface		Fat–Muscle Interface	
Frequency (MHz)	Wavelength in Air (cm)	Dielectric Constant	Conductivity (mmho/m)	Wavelength (cm)	Depth of Penetration[a] (cm)	magnitude	phase shift	magnitude	phase shift
1	30000								
10	3000								
27.12	1106	20	10.9–43.2	241	159	0.660	+174	0.651	+169
40.68	738	14.6	12.6–52.8	187	118	0.617	+173	0.652	+170
100	300	7.45	19.1–75.9	106	60.4	0.511	+168	0.650	+172
200	150	5.95	25.8–94.2	59.7	39.2	0.458	+168	0.612	+172
300	100	5.7	31.6–107	41	32.1	0.438	+169	0.592	+172
433	69.3	5.6	37.9–118	28.8	26.2	0.427	+170	0.562	+173
750	40	5.6	49.8–138	16.8	23	0.415	+173	0.532	+174
915	32.8	5.6	55.6–147	13.7	17.7	0.417	+173	0.519	+176
1500	20	5.6	70.8–171	8.41	13.9	0.412	+174	0.506	+176
2450	12.2	5.5	96.4–213	5.21	11.2	0.406	+176	0.500	+176
3000	10	5.5	110–234	4.25	9.74	0.406	+176	0.495	+177
5000	6	5.5	162–309	2.63	6.67	0.393	+176	0.502	+175
5900	5.17	5.05	186–338	2.29	5.24	0.388	+176	0.502	+176
8000	3.75	4.7	255–431	1.73	4.61	0.371	+176	0.513	+173
10000	3	4.5	324–549	1.41	3.39	0.363	+175	0.518	+174

[a] Depth for attenuation by 1/e.

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