LOS ALAMOS, NEW MEXICO 87544

OFFICE MEMORANDUM

TO : L. Rosen, MP-DO

DATE: December 21, 1970

FROM : Arvid Lundy, MP-1; Richard Hutson, MP-7

SUBJECT: DOSE TO PATIENT DURING HYPOTHETICAL MUONIC X-RAY IN VIVO TISSUE ANALYSIS

SYMBOL : MP-7-20

Patient Dose During Muonic X-Ray Tissue Analysis

Calculation is based on a hypothetical use where one irradiates a 1 cm^3 volume of tissue located at a depth of 10 cm in soft tissue. (This corresponds to the use of a mono-energetic 44 MeV pencil beam of muons.) It is assumed that the x-ray detector can be located within 20 cm of the stopping region, that the x-rays pass through 10 cm of tissue, and that a close packed array of seven large (100 cc) Ge(Li) detectors is used. (Paralleling seven detectors will decrease energy resolution by a factor of 2.6, but the detector efficiency of 100 cc detectors will be considerably better at the higher energies than the 30 cc detectors which the composite spectra is based on.)

1) Number of muons required:

Looking at the composite spectra produced by J-11, it appears that at least 10^6 counts in the oxygen photopeak would be desirable

$$N = \frac{10^6 \text{(counts in oxygen photopeak)}}{0.68\left(\begin{array}{l}K_\alpha \text{ oxygen yield per} \\ \text{tissue captured} \\ \text{muon}\end{array}\right) \times 0.217 \left(\begin{array}{l}\text{x-ray transmission} \\ \text{thru 10 cm tissue}\end{array}\right) \times 0.90\left(\begin{array}{l}\text{Ge(Li) detector} \\ \text{photopeak eff.} \\ \text{of 133 keV}\end{array}\right) \times 0.027 \left(\begin{array}{l}\text{geometrical} \\ \text{eff.*}\end{array}\right)} = 2.8 \times 10^8 \text{ muons.}$$

Required patient irradiation time:

$$\frac{2.8 \times 10^8 \text{ muons}}{3 \times 10^5 \frac{\text{muons}}{\text{sec cm}^2} \left(\begin{array}{l}\text{Expected LAMPF} \\ \text{muon yield for} \\ \text{prescribed conditions}\end{array}\right)} = 9.3 \times 10^2 \text{ sec} = 15.5 \text{ minutes}$$

*Geometric efficiency calculation:

$$G.E. = \frac{\Omega}{4\pi} = \frac{\frac{A}{r^2}}{4\pi} = \frac{7\ (\text{detectors}) \times \frac{\pi \times (2.5\ \text{cm}^{\dagger})^2}{(20\ \text{cm})^2}}{4\pi} = 0.027$$

†Front entrance radius of presently available 100 cc GeLi detectors.

2) Direct Muon Dose:

$$D_m = \frac{2.8 \times 10^8\ \text{muons} \times 44.0 \times 10^6\ \frac{\text{ev}}{\text{muon}} \times 1.6 \times 10^{-12}\ \frac{\text{ergs}}{\text{ev}}}{100\ \frac{\text{erg}}{\text{gm rad}} \times 10\ \text{gm}^{**}} = 19.7\ \text{rads}$$

**The incoming beam is visualized as a square 1 cm by 1 cm beam penetrating 10 cm into soft, unit density tissue.

Because of the higher LET in the muon stopping region the dose is not uniformly distributed. Study of muon range-energy curves shows the dose in the stopping region to be approximately 45 rads relatively to approximately 13.5 rads in the first few centimeters at the entrance region.

3) Muon Decay Dose:

Estimate that 65% of the muons decay prior to nuclear capture. (This is a function of Z, for Z = 11 the probability of decay is 0.5 and for Z = 8, 0.75.)

$$2.8 \times 10^8\ \text{muons} \times 0.65 \left(\begin{matrix}\text{fraction}\\ \text{decaying}\end{matrix}\right) = 1.8 \times 10^8\ \text{decay electrons.}$$

Assume an average decay electron energy of 25 MeV and an electron LET of 2 MeV/cm. Assume each electron to traverse approximately 0.5 cm in the stopping region.

1.8×10^8 electrons $\times$ 2×10^6 ev/cm $\times$ 0.5 cm $\times$ 1.6×10^{-12} ergs/ev / 100 ergs/gm rad $\times$ 1 gm = 2.9 rads

4) Dose Due to Nuclear Capture and Subsequent Nuclear Decay:

Assume 35% of the muons undergo nuclear capture. For C, N, and O the probability of charged particle emission is 0.15 with 50% of the particles being deuterons with estimated average energy of

15 MeV.* For dosimetry purpose assume all the particles to be 15 MeV deuterons. The range of a 15 MeV deuteron in tissue is < 1 cm so essentially all will be stopped in the muon stopping region.

$$D_n = \frac{2.8 \times 10^8 \text{ muons} \times .35 \begin{pmatrix}\text{nuclear}\\ \text{capture}\\ \text{fraction}\end{pmatrix} \times .15 \begin{pmatrix}\text{charged}\\ \text{particle}\\ \text{emission fraction}\end{pmatrix} \times 15 \times 10^6 \frac{\text{ev}}{\text{particle}} \times 1.6 \times 10^{-12} \frac{\text{ergs}}{\text{ev}}}{100 \frac{\text{erg}}{\text{gm-rad}} \times 1 \text{ gm}} = 3.5 \text{ rad}$$

5) Total Dose in the Stopping Region:

	Quality Factor†	REMS
Direct Muon Dose = 45 rads x	3	135
Muon Decay Dose = 2.9 rads x	1	2.9
Nuclear Emission Dose = 3.5 rads x	7	24.5
		162.4 REMS

†Quality factor assigned per UCRL-19382 based on LET in water.

Compare this dose with the dose administered during a thyroid scan with I-131. A typical thyroid scan with I-131 results in a whole thyroid dose of 1.3 rads/μc in[1] standard man with typically 100μc being[2] administered, i.e., 130 REMS. Therefore, it appears that the dose suggested in muonic activation is probably tolerable for many uses although certainly not desirable. It appears that the key to reducing dose is in achieving better geometrical efficiency and developments in Ge(Li) detector technology may make this feasible. If one considers looking at calcium in bone the situation would look much better because the calcium concentration in bone is 10 times that in "standard man." One might also be able to use a large NaI(Tl) detector with greatly increased detector efficiency.

RLH for Lundy

Arvid Lundy, MP-1

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RLH

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[1]Wagner, Principles of Nuclear Medicine, Philadelphia '68, Pg 774.

[2]Silver, Nucleonics, August '65.

* This data from Vaisenberg, et al, JETP 1, 467.

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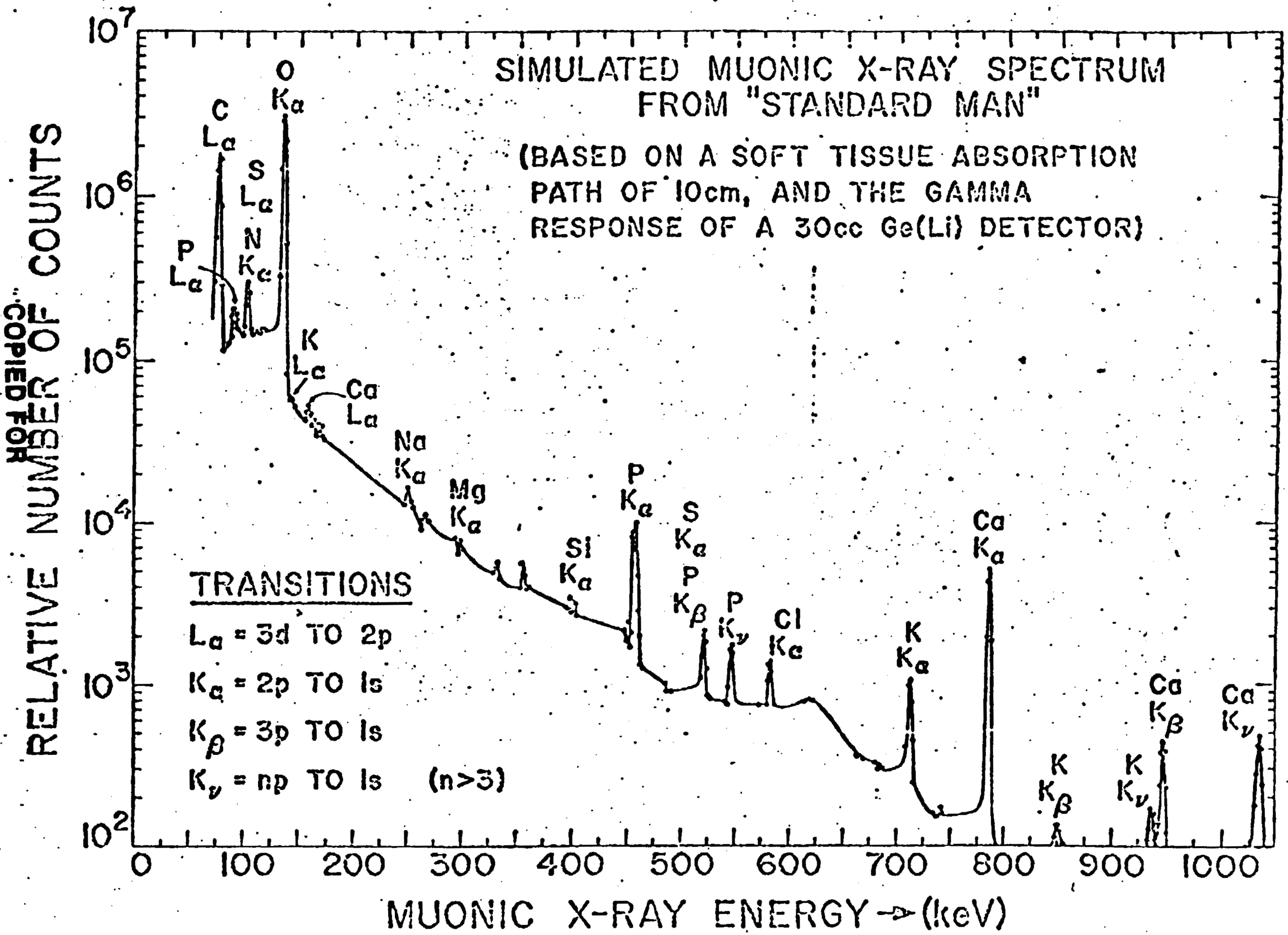
Table giving number of counts in photopeaks from muonic activation of "Standard Man" using 30 cc GeLi detector and applying corrections for detector efficiency vs energy and soft-tissue absorption path of 10 cm. (Normalized to 10,000 counts in Oxygen K_α photopeak.)

	Element and X-ray Line		Energy (keV)	Number of Counts
1.	Oxygen	L_α	24.0	2,295.
2.	Carbon	K_α	75.5	6,280.
3.	Phosphorus	L_α	88.0	193.
4.	Sulphur	L_α	100.	32.5
5.	Nitrogen	K_α	102.	549.
6.	Chlorine	L_α	113.	16.9
7.	Oxygen	K_α	133.	10,000.
8.	Potassium	L_α	140.	23.9
9.	Calcium	L_α	158.	150.
10.	Fluorine	K_α	168.	.421
11.	Sodium	K_α	250.	10.7
12.	Iron	L_α	264	.382
13.	Magnesium	K_α	296	2.04
14.	Zinc	L_α	356.	.152
15.	Silicon	K_α	400.	1.17
16.	Silicon	K_β	450.	.105
17.	Phosphorus	K_α	458.	42.4
18.	Silicon	K_γ	460.	.157
19.	Sulphur	K_α	522.	6.59
20.	Phosphorus	K_β	523.	3.56
21.	Phosphorus	K_γ	548.	5.24
22.	Chlorine	K_α	583.	3.49
23.	Sulphur	K_β	618.	.601
24.	Sulphur	K_γ	666.	.869
25.	Chlorine	K_β	683.	.295
26.	Potassium	K_α	713.	5.13
27.	Chlorine	K_γ	738.	.402
28.	Calcium	K_α	786.	33.0
29.	Potassium	K_β	851.	.271
30.	Potassium	K_γ	936.	.469
31.	Calcium	K_β	946.	2.25
32.	Calcium	K_γ	1034.	3.20
33.	Iron	K_α	1262.	.0690
34.	Zinc	K_α	1615.	.0320
35.	Iron	K_γ	1706.	.0144



SIMULATED MUONIC X-RAY SPECTRUM
FROM "STANDARD MAN"
(BASED ON A SOFT TISSUE ABSORPTION
PATH OF 10cm, AND THE GAMMA
RESPONSE OF A 30cc Ge(Li) DETECTOR)
TRANSITIONS
Lα = 3d TO 2p
Kα = 2p TO 1s
Kβ = 3p TO 1s
Kν = np TO 1s (n>3)
RELATIVE NUMBER OF COUNTS
MUONIC X-RAY ENERGY → (keV)

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