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THE RELATIVE EFFECTIVENESS OF FISSION NEUTRONS FOR MINIATURE PIG PERFORMANCE DECREMENT

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FOREWORD
(Nontechnical summary)

As neutrons can contribute substantially to the initial radiation dose from nuclear weapons, the currently reported study had as its objective the determination of the effectiveness of fission neutrons for performance decrement and incapacitation in the miniature pig.

Miniature pigs are used extensively as research animals at AFRRI for a variety of reasons. For example, their intestinal and cardiovascular systems have many similarities to those of man, they are easily trained to perform simple tasks, and as young adults they average 30 to 40 kg in weight with a trunk thickness of about 20 cm so that distribution of radiation dose through much of their body resembles that of a standard man exposed under the same conditions. Further, miniature pig performance decrement and incapacitation following pulsed mixed gamma-neutron irradiation has been previously studied in depth at AFRRI.

Miniature pigs, trained to cross a shuttlebox on cue, were supralethally irradiated in a nuclear reactor-produced neutron field; their postirradiation performance was compared to that of pigs similarly irradiated in either a gamma ray field or a mixed gamma-neutron field produced with the same reactor. The neutron field consisted of approximately 90 percent neutrons and 10 percent gamma rays; the gamma field was about 5 percent neutrons and 95 percent gamma rays; the mixed field was about 30 percent neutrons and 70 percent gamma rays. Since it had been shown that radiation damage to head structures was the cause of early permanent incapacitation, early transient incapacitation (ETI), and early death in these pigs, dose to the

middle of the brain was used as the reference for comparisons. The dose rate at that point was approximately 2000 rads/min for all irradiations and doses ranged from 1500 to over 36,000 rads. Distribution of dose across the brain and ratio of midbrain to midtrunk doses did not vary greatly among the neutron, gamma, and mixed field irradiations.

The miniature pig's response to the fission neutron field was quite different from its response to similar doses from the gamma ray field. Early performance decrement, including ETI and early permanent incapacitation, occurred following much lower doses from the gamma field than from the neutron field. Also the neutron-irradiated pigs lived longer on the average than did the gamma-irradiated pigs at doses greater than 11,000 rads. The response of animals to a given dose from the mixed field was generally intermediate in severity between the responses of the neutron- and the gamma-irradiated animals.

It was clear from the results of this study that the central nervous system damage in the miniature pig which is manifested by severe early performance decrement and death within 48 hours is more efficiently produced by gamma rays than by fission neutrons at high dose rates. The relative effectiveness of the fission neutron field was 0.23 using the reactor-produced gamma ray field as the reference radiation and the ED_{50} or 50 percentile dose for early performance decrement as the biological end point.

ABSTRACT

Trained miniature pigs were whole-body irradiated in a nuclear reactor-produced neutron field (incident neutron to gamma ratio of 10). Their postirradiation performance was compared to that of pigs similarly irradiated in a gamma ray field from the same reactor (incident neutron to gamma ratio of 0.06). The dose rate at the midline of the brain was approximately 2000 rads/min for all irradiations; midbrain doses ranged from 1500 to 36,500 rads. Response of the pigs to supralethal doses from the neutron field notably differed from their response to similar doses from the gamma ray field. Early performance decrement, early transient incapacitation, and immediate permanent incapacitation occurred following much lower doses from the gamma ray field than from the neutron field. At doses greater than 11,000 rads, survival times of the neutron-irradiated pigs were on the average much longer than those of the gamma-irradiated pigs. Thus, the gamma rays were markedly more effective than the fission neutrons for producing the severe central nervous system damage manifested by pronounced early performance decrement and death within 48 hours. The relative effectiveness of the neutron field was 0.23 using the reactor-produced gamma ray field as the reference radiation and the 50 percentile midbrain dose (ED_{50}) for early performance decrement as the biological end point.

I. INTRODUCTION

The response of trained miniature pigs to pulsed, supralethal doses (1000 to 15,000 rads) from a mixed gamma-neutron radiation field has been described.[5] Early transient incapacitation (ETI), consisting of severe convulsions and sometimes coma, occurred immediately after doses of 2400 to 12,000 rads. An interval of less pronounced performance decrement followed during which the condition of the pigs improved; satisfactory performance levels were generally achieved within 30 minutes postirradiation. The succeeding period of satisfactory performance terminated in a progressive performance decrement with permanent complete incapacitation (PCI) occurring a few hours before death. A threshold for very early death (less than 4 hours postirradiation) was evident at about 5000 rads. Data obtained in partial body shielding experiments indicate that ETI, early PCI, and very early death are the result of radiation damage to head structures.[9]

Early transient performance decrement (ETPD), including ETI, has been observed in other mammalian species,[3,4,11] and it is suggested that the response of humans to massive, supralethal doses of ionizing radiation would include such alterations in ability to function effectively.

As massive neutron exposures are possible under a variety of circumstances, the currently reported study had as its objective the determination of the effectiveness of fission neutrons for performance decrement and incapacitation in the miniature pig.

Miniature pigs, trained to cross a shuttlebox on cue, were supralethally irradiated in a nuclear reactor-produced neutron field; their postirradiation

performance was compared to that of pigs similarly irradiated in either a gamma ray field or a mixed gamma-neutron field produced with the same nuclear reactor.

II. MATERIALS AND METHODS

Animals. The experimental subjects were 127 miniature pigs of the Hormel and Hormel-Hanford strains. At the time of irradiation they were approximately 6 months old, weighed an average of 33.5 ± 3* kg, and had a mean body thickness of 20.5 cm at the shoulders. Males, females, and barrows were used.

Training. The pigs were trained by shock avoidance conditioning to traverse on cue a two-chambered shuttlebox.[5] Each trial lasted 13 seconds and consisted of a 6-second period during which visual and auditory cues were presented, a 4-second period when the cues continued while an electrical shock was applied to the animal, and a rest period. As soon as a test subject crossed the box, the cues (and shock when it was on) were discontinued and the rest period commenced. When a pig crossed the box during the first 6 seconds of a trial (before the shock was initiated), it was credited with an avoidance. When the pig crossed while the shock was being applied, it was credited with an escape. A failure was scored when the pig neither avoided nor escaped from the shock. Before irradiation the pigs were trained to a minimum performance criterion of 90 percent avoidance.

Irradiation. The radiation source was the AFRRI-TRIGA reactor. In an unmodified configuration, the radiation field is characterized by a neutron to gamma ray tissue kerma, free-in-air, of approximately 0.4. The neutron radiation field was obtained using a gadolinium-cadmium absorber for thermal neutrons coupled with

* Standard deviation

6 inches of lead shielding to minimize the gamma component of the field. The contribution of room-scattered gamma rays to the field was reduced by a shield of laminated wood, boron and lead. The gamma ray field was obtained by using 5 inches of water shielding and the same gadolinium-cadmium absorber. Neutron to gamma ray ratios, free-in-air, of 10 and 0.06 were obtained for the neutron and gamma ray fields, respectively. The exposure array for the neutron field is depicted in Figure 1.

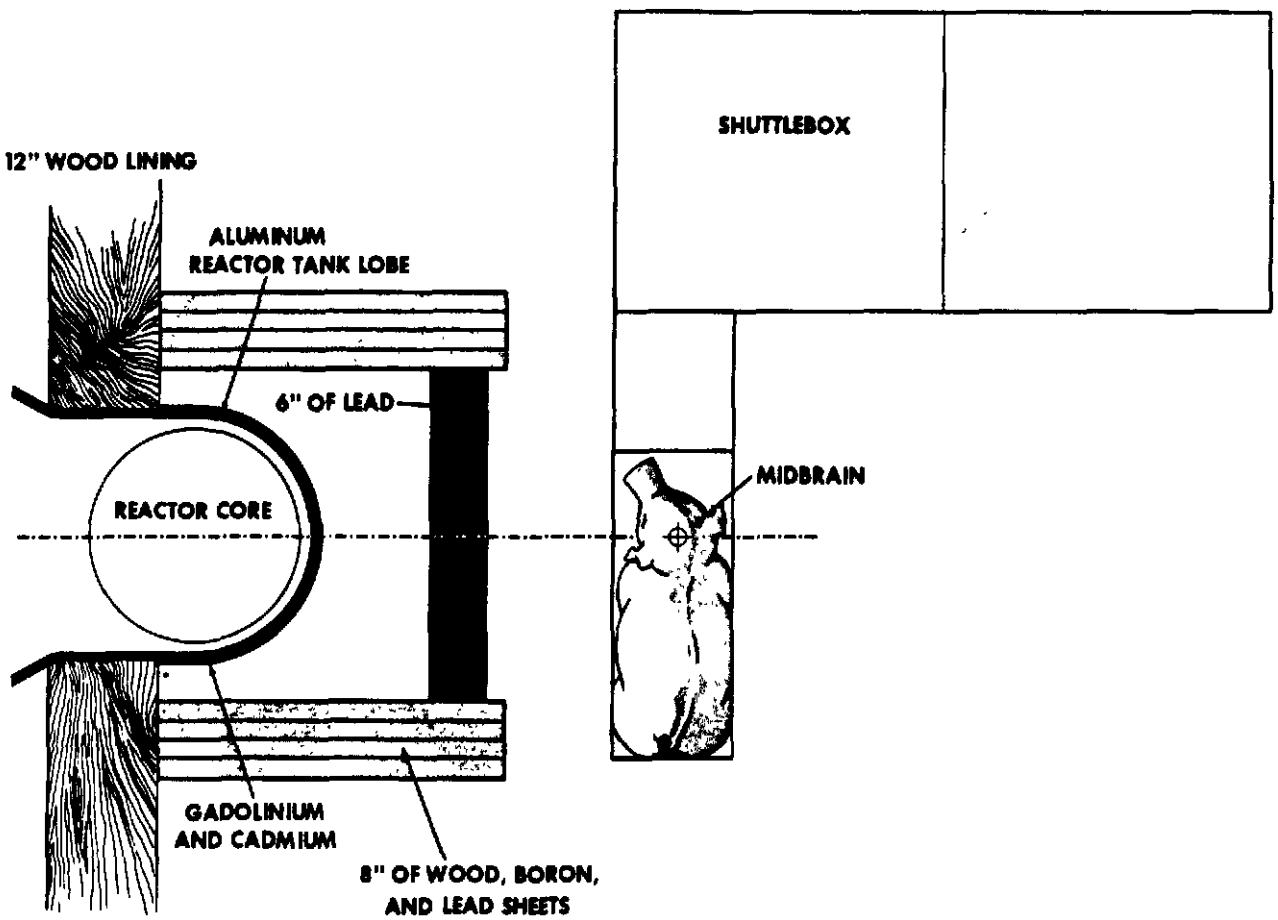

Figure 1. Exposure array for the neutron field

Depth-dose patterns across the brain region of a miniature pig cadaver were measured with miniature tissue-equivalent ionization chambers.[8] The dosimetry aspects of this research project are reported separately.[10]

Table I summarizes the depth-dose patterns across the brain region as well as the relationship between midbrain and midthorax doses for the neutron, mixed, and gamma ray fields. Entrance dose to exit dose ratios in the brain region are 2.2, 1.7, and 1.5, respectively, for the three fields.

Table I. Depth-Dose Pattern across Brain Region of Pig

Probe location	Percent of midbrain dose		
	Neutron field	Mixed field	Gamma field
Brain entrance	140	130	120
Midbrain	100	100	100
Brain exit	63	75	78
Midthorax	62	80	74

Each pig was irradiated unilaterally from the left side with the reactor operated in the steady-state mode. The dose rate at the midline of the brain was approximately 2000 rads/min for all radiation fields (the highest practical dose rate attainable with the neutron field). Miniature ion chamber and sulfur pellet monitors were normalized to midbrain doses measured in the cadaver. Midbrain doses for the experimental subjects were reported based upon the response of these monitors.

Midbrain doses were 1510 to 16,400 rads from the gamma field, 5900 to 36,500 rads from the neutron field, and 1600 to 24,700 from the mixed gamma-neutron field. The data obtained with the first 72 pigs irradiated (36 in the neutron field and 36 in

the gamma field) were used to estimate the relative effectiveness of fission neutrons for performance decrement. Performance data for the first 30 minutes postirradiation were used as the end point for comparison. A total of 90 avoidances was possible during this period with a minimum of 81 established as satisfactory. The most probable dose that would cause 50 percent of the animals to perform unsatisfactorily (ED_{50} or 50 percentile) was calculated by probit analysis for both the neutron and the gamma fields. Relative effectiveness = ED_{50} from the gamma ray field ÷ ED_{50} from the neutron field.

To more precisely determine the ED_{50} values, 26 additional pigs were irradiated employing the "up-and-down design" or "Bruceton" method[6] and the same biological end point. In addition, 29 pigs were exposed to the unaltered mixed gamma-neutron field to corroborate the calculated relative effectiveness of fission neutrons for performance decrement.

The pigs were released into the shuttlebox immediately after irradiation and were tested at 0, 2-1/2, 5, 7-1/2, 10, 15, 20, 25, 30, and 45 minutes, at each hour postirradiation for approximately 4 hours, and thereafter at 2-hour intervals until death, except that the 26 animals used only in the "up-and-down design" were tested on a less frequent schedule after 30 minutes postexposure. Each postirradiation test period consisted of 10 trials.

III. RESULTS

Early postirradiation symptoms of gamma and of mixed gamma-neutron irradiated pigs were similar to those previously described for pulsed, mixed gamma-neutron irradiations and included convulsions, coma, and ataxia.[5] Convulsions and coma were infrequently seen during ETI of the neutron-irradiated pigs; ataxia was

consistently evident, however, and these animals appeared to be disorientated and confused.

Miniature pig postirradiation performance is presented in Tables II-V. Figures 2 and 3 summarize the first 30-minute postirradiation performance data and mean survival time data for all dose groups, respectively.

In Tables II-IV, a pig was scored incapacitated when it convulsed violently, collapsed, or otherwise failed to cross the shuttlebox on several consecutive trials. A pig was scored as suffering performance decrement when it avoided the shock less than 9 times out of the 10 possible in a given test period.

The data in Tables II and III reveal that the miniature pig's response to supralethal doses from the fission neutron field markedly differed from the response to similar doses from the gamma ray field. In the gamma-irradiated pigs, ETI was observed in all dose groups of 2500 rads or more, and 23 of 24 pigs receiving 4500 to 16,400 rads had ETI; ETI did not occur in the neutron-irradiated groups at doses less than 9500 rads, and only at doses greater than 25,700 rads did all subjects suffer ETI. Immediate permanent incapacitation frequently occurred following doses of 10,700 to 16,400 rads from the gamma field, but was not seen at doses less than 28,500 rads from the neutron field. Essentially none of the gamma-irradiated pigs performed satisfactorily following 16,000 rads; whereas, at least half of the animals in each of the neutron-irradiated groups performed satisfactorily for some time following doses up to and including 25,700 rads. Average survival times of the neutron-irradiated pigs were markedly longer than those of gamma-irradiated pigs at equivalent doses greater than 11,000 rads (Figure 3).

Table II. Performance of Neutron-Irradiated Miniature Pigs

Midbrain dose (rads)	Duration of ETI* (min)	Duration of ETPD* (min)	Avoidances during first 30 min postirradiation	Duration of satisfactory performance (h)	Survival time (h)
5,900	none	none	90	51	58
5,900	none	none	89	68	74
7,800	none	none	90	80	95
7,700	none	none	88	57	76
7,700	none	none	90	48	52
7,700	†	†	†	54	64
9,400	none	none	89	32	35
9,500	11	12	41	53	78
9,600	none	none	88	52	58
9,600	none	<1	86	50	78
11,200	10	30	35	21	40
11,200	none	none	89	36	56
11,100	none	none	88	34	54
11,300	3	3	78	47	57
14,800	none	none	88	35	39
14,600	6	45	59	15	53
14,900	10	90	68	~24	62
15,200	none	4	83	33	43
18,200	2	3	77	8	31
18,300	8	IPPD*	54	0	8
18,400	~10	~10	68	0.2	22
18,500	6	15	65	0.5	10
21,400	~3 h	IPPD	0	0	33
21,200	~1 h	IPPD	14	0	41
21,300	none	none	85	31	44
21,500	none	6	79	7	14
24,900	none	8	79	0.5	16
25,100	8	IPPD	21	0	12
25,800	~4 h	IPPD	14	0	27
25,700	none	16	71	2	14
29,600	IPI*	IPPD	2	0	16
29,500	IPI	IPPD	7	0	10
29,600	8	IPPD	30	0	12
28,500	IPI	IPPD	18	0	18
36,500	IPI	IPPD	0	0	14
36,100	IPI	IPPD	2	0	6

* ETI Early transient incapacitation
ETPD Early transient performance decrement (includes ETI period)
IPI Immediate permanent incapacitation
IPPD Immediate permanent performance decrement (includes IPI)
† Equipment failure resulted in loss of data during first 10 minutes

Table III. Performance of Gamma-Irradiated Miniature Pigs

Midbrain dose (rads)	Duration of ETI* (min)	Duration of ETPD* (min)	Avoidances during first 30 min postirradiation	Duration of satisfactory performance (h)	Survival time (h)
1,620	none	none	88	107	109
1,570	none	none	89	95	96
1,510	none	none	90	~120	~125
1,550	none	none	90	~120	~124
2,500	none	none	90	113	118
2,500	1	2	83	111	118
2,600	9	12	49	72	74
2,600	none	4	84	105	114
3,600	none	none	90	94	98
3,800	8	10	54	~120	~127
3,600	12	16	38	102	108
3,600	none	2	84	101	109
4,500	2	5	78	109	122
4,500	26	30	17	90	104
4,500	8	13	47	101	108
4,500	8	12	50	112	121
6,600	8	15	49	102	107
6,600	16	25	29	62	73
6,500	3	9	58	94	98
6,600	3	10	72	93	98
8,600	8	15	40	82	94
8,800	8	16	44	103	107
8,800	17	28	19	58	65
8,900	2	3	80	1	4
11,000	30	90	3	41	56
10,800	21	35	19	57	69
10,900	none	12	71	50	57
10,700	IPI*	IPPD*	0	0	10
12,400	8	14	50	~10	20
12,400	IPI	IPPD	0	0	24
12,500	11	18	36	56	72
12,500	IPI	IPPD	6	0	4
16,400	IPI	IPPD	0	0	9
16,400	20	25	18	0.2	20
16,300	IPI	IPPD	1	0	6
16,200	20	IPPD	14	0	10

* ETI Early transient incapacitation
ETPD Early transient performance decrement (includes ETI period)
IPI Immediate permanent incapacitation
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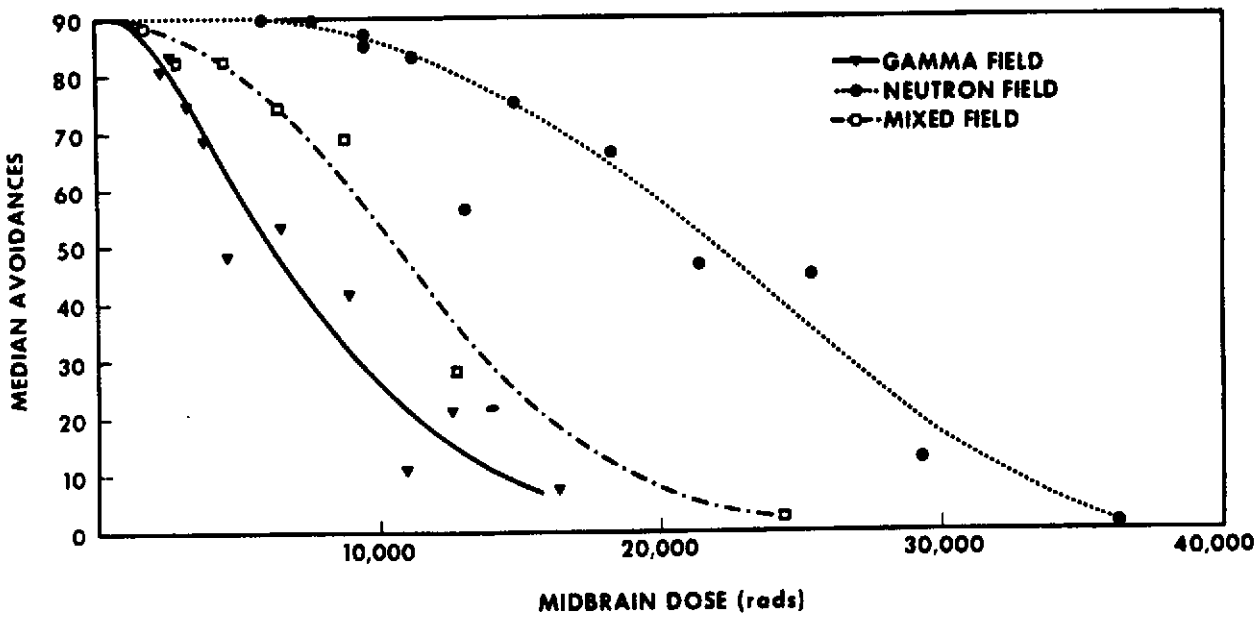

Figure 2. Median number of shock avoidances during first 30 minutes postirradiation

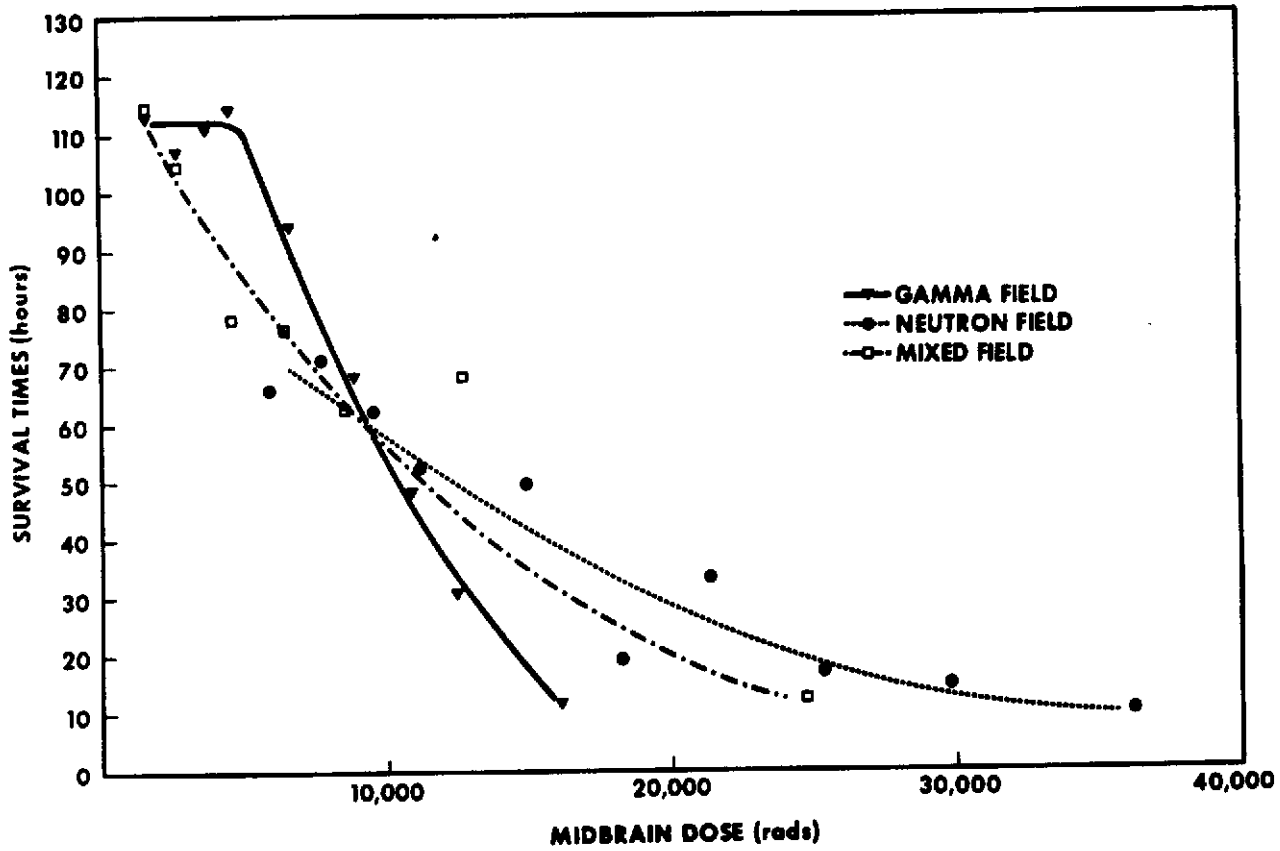

Figure 3. Mean survival times

Probit analysis of the performance data from the initial 72 pigs irradiated (using the first 30 minutes postirradiation as a single test period and 90 percent avoidances as minimum performance criterion) resulted in ED_{50}'s of 3180 rads for the gamma ray field and 13,000 rads for the neutron field. From these results the relative effectiveness for the fission neutron field with respect to the ED_{50} for early performance decrement was estimated to be 0.24.

Data from the mixed gamma-neutron irradiations (Table IV) support the findings from the neutron and the gamma irradiations in that the response to a given dose was consistently intermediate between the responses obtained with equivalent doses from the neutron field and from the gamma ray field (Figures 2 and 3). Probit analysis of the first 30-minute postirradiation performance data resulted in an ED_{50} of 4200 rads from the mixed field. This ED_{50} is in good agreement with the ED_{50}'s calculated for the neutron and gamma fields, using the neutron-gamma ratios of the three fields as the basis for comparison (Figure 4).

Table V contains data used in the "up-and-down design" calculations. For this analysis, the first 30 minutes postirradiation was considered as one test period. These data produced ED_{50}'s of $2500 \times\div 1.53$ rads for the gamma field and $11,000 \times\div 1.19$ rads for the neutron field. The relative effectiveness of the neutron field at the ED_{50} points was, therefore, 0.23. The two ED_{50}'s were significantly different ($p<0.1$). Furthermore, with a confidence of 95 percent, the neutron field ED_{50} was within the interval of 9600 to 12,600 rads, and the gamma ray field ED_{50} was within

Table IV. Performance of Mixed Gamma-Neutron Irradiated Miniature Pigs

Midbrain dose (rads)	Duration of ETI* (min)	Duration of ETPD* (min)	Avoidances during first 30 min postirradiation	Duration of satisfactory performance (h)	Survival time (h)
1,600	0	3	84	114	119
1,600	0	0	88	101	104
1,600	0	0	90	110	117
1,600	0	0	90	112	117
2,700	3	5	74	112	116
2,700	0	0	89	88	90
2,700	0	0	89	111	116
2,800	5	27	38	92	95
3,700	0	0	88	96	105
4,400	0	0	88	72	80
4,500	0	0	88	74	79
4,600	3	9	59	~80	~85
4,600	2	3	76	63	68
6,300	2	8	67	71	85
6,400	10	12	41	51	55
6,400	0	0	87	72	82
6,300	1	2	80	78	84
8,600	0	0.5	86	63	67
8,600	0	7	71	60	68
8,600	16	21	38	49	59
8,700	5	6	66	46	56
12,700	40	3 h	24	~24	57
12,800	16	27	25	50	90
12,700	12	IPPD*	47	0	55
12,700	12	40	30	54	72
24,300	IPI*	IPPD	0	0	12
24,500	IPI	IPPD	0	0	9
24,100	IPI	IPPD	9	0	17
24,700	IPI	IPPD	5	0	10

* ETI Early transient incapacitation
ETPD Early transient performance decrement (includes ETI period)
IPI Immediate permanent incapacitation
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the interval of 1865 to 3380 rads.* All ED_{50} calculations utilized the logarithm of dose versus response.

* Statistical analyses accomplished by S. G. Levin, mathematical statistician, Mathematical Analysis Division, Physical Sciences Department

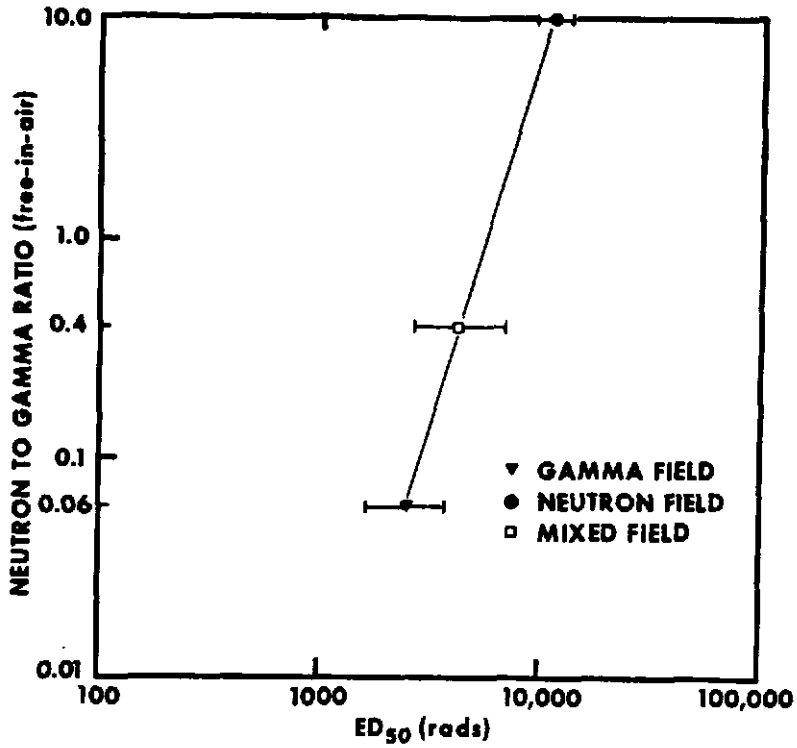

Figure 4. ED_{50} for early performance decrement versus neutron-gamma ratio, free-in-air. (Error bar indicates 95 percent confidence interval.)

Table V. "Up-and-Down Design" Data. Each succeeding animal is tested at the dose level one step below the dose used in the preceding test if it resulted in unsatisfactory performance, or at the dose level one step above if it resulted in satisfactory performance.

Dose from Gamma Field (rads)	Shock Avoidances during first 30 min postirradiation in consecutive animals (90 possible)
4,500	50 47 17
3,100	65 **83** 42 50 **85** **84** 75
2,100	**88** **90** 65 66 * 75 **89**
1,500	**90** **90** **89** **88**
Dose from Neutron Field (rads)	
18,500	68
13,100	31 77 55 73 56 **87** 33
9,500	**88** 41 **88** **86** **85** **89** 49
6,800	**88**

Underlined data are from pigs whose performance was evaluated on the regular basis until death and are included in Tables II and III.

Bold type indicates satisfactory performance.

* Equipment failed during part of the test period, however, animal missed more than 10 trials.

Entrance to exit dose ratios in the brain were 2.2 and 1.5, respectively, for the neutron and gamma irradiations. The minimum dose in the brain (exit side) was approximately 63 percent of the reported midbrain value for neutron-irradiated pigs; for gamma irradiations the minimum brain dose was about 78 percent of the reported midbrain dose. If minimum dose in the brain were a better parameter upon which to base relative effectiveness calculations, the relative effectiveness for early performance decrement would be approximately 0.28, a value not markedly different from the 0.23 obtained using midline brain doses.

If one finds it more convenient to evaluate effects with regard to exposure conditions rather than absorbed energy, the relative effectiveness of the neutron field would be approximately 0.15 (tissue-air ratios at the middle of the brain were 0.57 for the neutron irradiations and 0.82 for the gamma irradiations).

IV. DISCUSSION

Preliminary data* indicate the ratios of neutron kerma to gamma kerma in the brain of the neutron-irradiated pigs were approximately 3.2, 2.3, and 1.9 near the entrance, middle, and exit, respectively. Thus the maximum gamma dose in the brain was generally as great or greater from the neutron field as from the gamma field for a given degree of performance decrement; i.e., at the ED_{50}, maximum brain gamma doses are estimated to be 3000 and 3400 rads for the gamma and the neutron irradiations, respectively. Further, at the position occupied by the center of the pig's brain, the gamma kerma, free-in-air, from the mixed field was in many

* Unpublished: Verrelli, D. M., Armed Forces Radiobiology Research Institute, Bethesda, Maryland

instances at least as great as that required from the gamma field to achieve a given degree of performance decrement. The neutron and gamma components of dose thus appear in general not to be additive with regard to the early performance decrement response.

The low relative effectiveness of the neutron field (as defined in this report) is probably due to much of the absorbed energy from neutron produced high linear energy transfer (LET) particles being wasted; however, the dose rate in the brain from the gamma component of the neutron irradiations was considerably lower than that of the gamma irradiations and could have contributed to the low effectiveness. The apparent lack of additivity for the separate components of the mixed and of the neutron fields was likely due to the gamma dose rate difference.

If more energy depositions are produced in a target volume than are sufficient for inactivation, the extra energy depositions are "wasted" and may be thought of as overkill. The concentration of energy deposited by high LET particles in the targets responsible for performance decrement may have resulted in such wasted energy.

The effect of dose rate on radiation response has been examined in some detail and was recently reviewed.[2] However, study of the dose rate dependence of performance decrement has been largely limited to low dose rates. The generalization that a radiation dose delivered over a long period of time is less effective than the same dose delivered over a short period of time, and the apparent lack of additivity for neutron and gamma doses in the currently reported study, lead to the suggestion that performance decrement varies with gamma ray dose rate even at hundreds to thousands of rads per minute. This hypothesis is presently under investigation.

Mechanisms by which gamma photons are more effective in causing miniature pig performance decrement have not yet been elucidated. However, it is suggested that performance decrement from high doses of ionizing radiation is a consequence of marked alterations in the excitability and conductivity characteristics of neurons. Evidence obtained using excised frog sciatic nerves indicates both nerve conduction velocity and nerve excitability increase during and for some time after x irradiation at high dose rates (1400 and 2800 rads/min).[7] Increased excitability of neurons could result in nerve action potentials (NAP) arising from the continual release of small quanta of neurotransmitters which occurs spontaneously from presynaptic stores but is normally insufficient to elicit a postsynaptic NAP. Many of the gamma-irradiated pigs began to convulse or exhibited severe muscle tremors when electrically shocked in the test box (a procedure that caused no such extreme neurological manifestations in the unirradiated animals), an indication of increased excitability.

A possible target responsible for increased nerve excitability is the active (carrier-mediated) transport mechanism for sodium in the nerve membrane. Inactivation of the postulated carrier molecules, carrier-sodium complex degrading enzymes, or the carrier activating system would lead to a higher Na^+ and lower K^+ intracellular concentration, and therefore a lower transmembrane potential and more easily depolarized nerve membrane. Such effects could possibly account for the increased electrical activity of the central nervous system required to initiate and maintain the convulsions previously described[5] and frequently seen in the gamma and mixed gamma-neutron irradiated pigs of this study. They might also explain

other neurological effects which contribute to the performance decrement such as ataxia, confusion, and coma.

The term "relative potency" has been used by others to describe what is herein called "relative effectiveness".[1] With radiation fields consisting of indirectly ionizing particles having a wide spectrum of energies and/or with a large absorbing specimen which very significantly perturbs the field, the term "relative biological effectiveness (RBE)" is not very appropriate.

V. SUMMARY

Clearly, the central nervous system damage manifested by severe early performance decrement and death within 48 hours in the miniature pig is more efficiently produced by gamma rays than by fission neutrons at high dose rates (approximately 2000 rads/min). The relative effectiveness for the modified fission spectrum neutron field is 0.23 using the reactor-produced gamma ray field as reference radiation and the ED_{50} for early performance decrement as biological end point.

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Trained miniature pigs were whole-body irradiated in a nuclear reactor-produced neutron field (incident neutron to gamma ratio of 10). Their postirradiation performance was compared to that of pigs similarly irradiated in a gamma ray field from the same reactor (incident neutron to gamma ratio of 0.06). The dose rate at the midline of the brain was approximately 2000 rads/min for all irradiations; midbrain doses ranged from 1500 to 36,500 rads. Response of the pigs to supralethal doses from the neutron field notably differed from their response to similar doses from the gamma ray field. Early performance decrement, early transient incapacitation, and immediate permanent incapacitation occurred following much lower doses from the gamma ray field than from the neutron field. At doses greater than 11,000 rads, survival times of the neutron-irradiated pigs were on the average much longer than those of the gamma-irradiated pigs. Thus, the gamma rays were markedly more effective than the fission neutrons for producing the severe central nervous system damage manifested by pronounced early performance decrement and death within 48 hours. The relative effectiveness of the neutron field was 0.23 using the reactor-produced gamma ray field as the reference radiation and the 50 percentile midbrain dose (ED_{50}) for early performance decrement as the biological end point.

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