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ACUTE SKIN LESIONS DUE TO LOCALIZED "HOT PARTICLE" RADIATION EXPOSURES*

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ABSTRACT

The purpose of these studies was to determine the incidence and severity of lesions resulting from very localized deposition of dose to the skin from small (< 0.5 mm), discrete radioactive particles. Hanford mini-swine were exposed to localized doses from 0.2 to over 600 Gy (averaged over 1 cm^2 at 70 μm depth) from isotopes having maximum beta particle energies from about 0.3-3 MeV. The incidence of erythema and scabs (indicating ulceration) were scored routinely for up to 71 days post-irradiation.

The responses followed normal probability distributions, and thus, no true threshold could be defined. Ten and 50% incidence rates were deduced using probit analyses. The lowest dose which produced 10% incidence was about 1 Gy for exposures to Yb-175 (0.5 MeV maximum energy) beta particles. The severity of lesions was estimated by analyzing the results in terms of their diameters and persistence. From preliminary considerations of the probability of induction, size, and persistence of acute lesions, a special limit for hot particle exposures in the range of 5-50 Gy may be reasonable, with an action level between about 1 Gy and the limit.

INTRODUCTION

Exposure to workers to small radioactive particles, typically ranging in size from one micron to a few hundred microns in diameter has been identified as a problem in the nuclear power industry. These particles have become known as "hot particles" due to their relatively high specific activity and small size. When deposited on the skin or inhaled, they can cause intense local irradiation of small areas of tissue and may cause reddening, ulceration, necrosis, and a possible increase in the risk of skin cancer.

In December 1989, the National Council on Radiation Protection and Measurements (NCRP) published a report which reviewed the effects of exposure to hot particles in a human volunteer, in monkeys, and pigs (1). Based on this review, a recommended limit of 10^{10} beta particles (75 μCi h; 10 GBq s) emitted from a "point" particle or a particle of less than 1 mm in diameter was suggested for particles in contact with the skin. This limit was intended to prevent "deep" ulceration but, admittedly, might allow transient effects which frequently disappear in less than a week, as observed by Hopewell et al. (2). For beta particles from activated fuel, this exposure causes a dose of about 5 Sv averaged over 1 cm^2 at a depth of 70 μm in tissue. The risk of skin cancer following irradiations of the skin by hot particles was deemed less than that when extended areas of the skin are irradiated due to the small number of cells exposed and the greater potential for cell killing from the localized beta particle dose.

In 1987, an International Commission on Radiological Protection (ICRP) Task Group reviewed much of the same material reviewed by the NCRP. However, the Task Group based its recommendations on preventing acute transient ulceration and recommended restricting to 1 Sv the dose delivered within a few hours over an area of 1 cm^2 measured between depths of 100-150 μm (10-15 mg/cm^2) (3). The latest recommendations of the ICRP, nevertheless, retain the limit of 500 mSv averaged over any 1 cm^2, at a nominal depth of 7 mg/cm^2, regardless of the area exposed (4). The objectives of this work were to provide additional scientific data to use in the decisions and recommendations of these committees and the regulatory agencies.

MATERIALS AND METHODS

Hanford mini-swine were exposed to four types of particles at Brookhaven National Laboratory (BNL): 1) activated UC_2 particles of 250 μm diameter for comparisons with the data of Forbes and Mikhail used in NCRP Report 106 (1); 2) Tm-170 particles with dimensions of about 230-500 μm for comparisons with Hopewell et al's data used extensively by the ICRP Task Group (3); 3) Yb-175 particles with dimensions of 280-500 μm and maximum beta particle energy of 0.5 MeV (to simulate Co-58 which emits a 0.47 MeV positron); and 4) Sc-46 with beta and gamma emissions very similar to those of Co-60. Cobalt-60, Co-58, and activated fuel are the commonest sources of hot particles in nuclear power plants. Scandium-46 was used rather than Co-60 because its shorter half-life and lower density allowed the production of particles that simulated 100-μm-diameter Co-60 particles with much shorter activation periods. UC_2 particles were 252-μm-diameter spheres coated with 18.5 μm of pyrolytic graphite. Other particles were cut from foils of thickness 258 μm (Tm), or 130 μm (Yb and Sc). The largest dimension of the latter pieces was 535 μm.

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Irradiations were made within tattooed grids on the flanks of anestisized pigs. Sources were mounted on styrofoam blocks to minimize backscatter. Exposures of 45 s or less were made using a hand-held cone/rod jig with the source fastened to the end of a styrofoam cone, 8 cm long, attached to a plexiglass rod 22 cm in length. Longer exposures were made using a cloth harness with elastic straps which flexed as the animal breathed, yet held the source in a fixed position for up to two hours.

UC_2 and Tm-170 particles were employed both touching the skin and slightly above the skin to test the hypothesis that more beta particles might be required to induce ulcers in the latter case which minimizes particles on clothing. Animals ranging in age from 3.8 to 15 months were exposed to see if age at exposure had any effect on the outcome. Various scoring procedures were explored to test the sensitivity of results to the number of observations per week, the number of number of observers, and the number of days of observation post-exposure. The sensitivity of results to background corrections also was studied. In addition, the diameter of any lesion and area of erythema was measured, using an overlaid scale, and their persistence recorded.

The following were the scoring procedures for erythema and scabs:

Method A, which detected the most lesions, is a modified Hopewell et al. (2) method in which the mini-swine were scored twice per week for 28 days using two or sometimes three observers (Hopewell, personal communication). To model this scoring criterion, we eliminated data from one of the three weekly observations for the first 21 days post-irradiation. Thereafter, BNL observers made only two observations per week, which was similar to the Hopewell scoring schedule. The BNL lesion-scoring criteria were as follows. If two observers scored an area as a lesion on the same day, or if two observers scored the area as a lesion on one day and one observer scored it as a lesion on the successive day, or visa-versa, the area was scored as one-half of a lesion. If two observers scored the area as a lesion on two consecutive days, then it was considered to be a full lesion.

Method B, or "4-of-6/4-of-4," gave fewer lesions than Method A. For the first three weeks in which the mini-swine were scored three times per week, a lesion was considered to be radiation-induced if two independent observers each scored an area as a lesion a minimum of twice in one week. This method was called 4-out-of-6, since there were two observers and three observation periods, giving six possible outcomes, and four scorings of a lesion were required out of the six possibilities, with each observer seeing the lesion at least twice. After the first 21 days, the pigs were scored twice per week, and a lesion was considered to be radiation-induced if two observers each scored a lesion on two consecutive observation days--which was called 4-out-of-4.

Method C, or "6-of-8/5-of-6," was the most restrictive scoring technique used, and was designed to minimize any spurious apparent background. A lesion was considered radiation-induced if two observers scored an area as a lesion three times each out of a possible four consecutive scoring periods for the first three weeks. After three weeks, when the pigs were only scored twice per week, and a lesion was considered radiation-induced if one observer scored an area as a lesion a minimum of two times and another observer scored the same area as a lesion a minimum of three times in three consecutive scoring periods.

RESULTS

Analysis of the results as a function of the animal's age at exposure revealed no single pattern of changes with age. There was greater variability in the results for specific doses in animals over about 10 months of age, however, individual differences in response were as large as those due to age.

Biopsy samples of normal skin were taken from animals of ages 3.8 months to 15 months. The thickness of the keratin layer ranged from 18-33 μm at ~3 months and increased to 48 μm in pigs aged 15 months. The depth of the basal layer varied from 56-92 μm for these young animals and was 100 μm for a single sample at 15 months of age.

The period of observation (28, 48, or 71 da) was very important. Deduced ED_{50} values (50% incidence of a barely detectable lesion or erythema) were 1.5 to 4 times higher for observations that continued for only 28 days compared to those continued for >71 days. The method of scoring (A, B, or C) typically caused differences of factors of about two, with Method C generally giving higher ED_{50} results; this is attributed to better discrimination against background, or the false positive results obtained using scoring Method C. Background effects (scabs in unexposed areas) were typically about 3%, but varied from 0-14% with large statistical uncertainties due to the small number scored (e.g., 1 of 28 spots). Correcting for background events typically caused 5-10% changes in ED_{50}, and 10-20% changes in ED_{10} results using scoring Method C.

Extrapolation of scab diameter results to the zero diameter intercept to arrive at an apparent threshold yielded results for UC_2 exposures of 4.4-9.1 Gy for exposures to particles on the skin. This compares to about 15 Gy for the related Forbes/Mikhail results. These results are approximately equal to the ED_{10} value of 8.5 Gy derived from the UC_2 incidence results, summarized below.

Table 1 summarizes the percentage scab incidence for the four particles studied here and compares them to the work of Hopewell (5) and Reece et al. (6). The most effective particle in our studies was Yb-175 with maximum beta particle emission of 0.47 MeV that yielded an ED_{10} value of 1.3 Gy (0.36 - 2.6 Gy at 95% confidence). Approximately equal ED_{50} values were obtained for Yb-175 and Tm-170 (0.97 MeV), 5.5 and 5.9 Gy, respectively. These values also are close to the value derived from Hopewell's studies (4.5 Gy) using Tm-170. Both Sc-46 and activated UC_2 had higher ED_{50} values, 12 Gy and 11 Gy, respectively. The ED_{50} values reported by Reece et al. (6) for Co-60,

Table 1. Comparison of the Findings of Hopewell et al., BNL, and EPRI*

Isotope	E_{max} (MeV)	E_{avg} (MeV)	Hopewell		BNL		Reece
			ED_{10} (Gy)	ED_{50} (Gy)	ED_{10} (Gy)	ED_{50}(Gy)	ED_{50} (Gy)
Pm-147	0.22	0.062	2.7	3.9			
Co-60	0.31	0.096					40
Sc-46	0.36	0.11			5.1	12	
Yb-175	0.47	0.12			1.3	5.5	
Tm-170	0.97	0.29	1.9	4.5	2.8	5.9	18
Sr/Y-90	1.4**	0.55	3.4	8.4			
U (act.)	1.8 (1.1)**	0.71 (0.4)			8.5	11.4	40

* Dose averaged over 1 cm^2 at 70 μm depth (Gy).

**Average of the maximum energies emitted by the isotopes in the source. Values in parentheses are for Reece's sources.

Tm-170, and activated U particles were 3-4 times higher than the corresponding results for Sc-46, Tm-170, and UC_2 from our studies and those of Hopewell et al. (5).

DISCUSSION AND CONCLUSION

The lesions being scored in this type of study at low doses are small (e.g., about 1- to 2-mm diameter), and transient (e.g., 1-2 weeks). These lesions are not open festering wounds, but rather, barely noticeable scabs. The question to answer is how should this detriment be weighted in comparison with the debilitating effects normally being avoided in setting limits for deterministic and stochastic risks.

In these studies, over 1,100 individual spots were exposed to hot particles. About 560 of these developed detectable scabs which were assumed to result from a break in the integrity of the skin, and therefore, may lead to infection. Only two of the exposed sites became infected -- these after exposures near 500 Gy. One was treated topically with ointment for a few days and the other was treated topically and systemically with an antibiotic since the lymph nodes seemed to be infected. These large exposures leading to infection certainly are not acceptable detriments and a limit should be set to avoid them. However, the low incidence of infection for animals living under typical experimental conditions, and lack of other serious effects, suggests that a limit set to avoid persistent ulceration may be acceptable even if small transient scabs are produced.

A dose limit could be based on the product of the probability of scab formation, the diameter of the scabs and their persistence. From a preliminary evaluation of our data, for doses in the range of 1-200 Gy, this value is about 1-4 scab-mm-da/Gy. Alternately, a limit could be based on the number of days a scab is expected, regardless of its diameter. For example, preliminary analysis in terms of the number of scab-days for exposures between 0.1 and 50 Gy indicates that an average value for all sources is about 1.6 scab-days/Gy with somewhat higher values at lower doses and perhaps twice as many scab-days per Gy from Tm-170 compared with other sources.

These results together suggest that a limit in the range of 5-50 Gy may be appropriate to avoid effects that are more nearly comparable with other detriments at the dose limits. Based on these results and the relatively small harm associated with the production of lesions by hot particles, it seems reasonable to set a special hot particle limit in the range of 5-50 Gy (dose averaged over 1 cm^2 at 70-μm depth in tissue). In addition, an action level for persons receiving doses in the range 1 Gy to the limit selected could be established involving weekly checks for possible lesions; any ones detected then could be treated to avoid infection.

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