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METHODS IN THE EVALUATION OF RADIATION HAZARDS
IN MANNED SPACE FLIGHT*

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In many respects, this discussion will belabor the obvious - that radiation hazards in manned space flight operations should be evaluated from a viewpoint not inflexibly prejudiced by present-day occupational radiation safety standards. Manned space flight is a new occupation, totally different from those for which existing standards were established, and a fresh approach is required.

This position does not ignore the decades of accrued experience that have been used by many experts in the definition of good practices of radiation safety for the occupationally exposed individuals as well as for the general population. Rather, the position notes that the occupational standards reflect the considerations that radiation is the single outstanding risk, that large numbers (in excess of 200,000 in the U.S.) will be in occupations involving radiation exposure, that an expanding nuclear energy industry and therefore threat of increased exposure is inevitable, and that the radiation sources or source materials are controllable.

In order to meet the objectives of large-scale radiation protection; " - - - to prevent or minimize somatic injuries and to minimize the deterioration of the genetic constitution of the population"⁽¹⁾, the concept of "permissible dose" became established. This dose is defined by the ICRP⁽¹⁾, as " - - - that which involves a risk that is not unacceptable to the individual and to the population at large", and which carries " - - - a negligible probability of severe somatic or genetic injury - - -" to the exposed individual. Although the objectives of space radiation

protection are certainly the same as those noted above, the framework of historical reference in which the standards evolved must be side-stepped to avoid the application of permissible doses that may be unnecessarily restrictive.

Are there valid reasons to justify an independent review of the hazards and the setting of new standards if deemed appropriate: We believe there are at least these good reasons:

1. The radiation hazard is only one of many recognized and accepted serious potential hazards that could jeopardize the success of any flight mission,
2. The population-at-risk is extremely small and volunteer (the latter factor does not imply that a justification for relaxing controls exists, but that part of the burden of control is automatically apportioned to any volunteer),
3. The exact time, rate, duration, radiation quality and frequency of exposure are largely unpredictable and uncontrollable requiring inclusion of on-board protective means in the form of shielding. Since this can create an undesirable weight penalty, the radiation risks must be balanced against those invoked by the equipment capability traded for shielding weight,
4. Each flight may have a different profile, and therefore a different risk versus benefit analysis sequence will be required.

These reasons and the experimental nature of present manned flight operations are obviously in conflict with the philosophy behind the occupational limits. Even the limit of 25 r for whole body exposure in unplanned emergencies is restrictive in magnitude and in the sense of the "once in a lifetime" permissiveness⁽²⁾.

In spite of the clear differences in requirements for radiation safety between the average atomic energy employee and the astronaut, the ICRP-NCRP recommendations^(1,2) have been utilized to form the basis of exposure limits for space flight operations⁽³⁾. This was accomplished by assuming the astronaut could receive the equivalent of the occupational lifetime accumulated permissible dose within the briefer period of a five-year flight career. This time scale compression along with other manipulations produced a set of exposure limits that by chance were partly sensible but were also quite arbitrary and devoid of flexibility.

The irony of it all is the simple fact that the Federal Radiation Council (FRC) position had been developed and quite clearly pointed out the flexible nature of the new look in protection standards⁽⁴⁾. In fact, the FRC introduced the flexible concept of the Radiation Protection Guide (RPG) which is defined as " - - - the radiation dose which should not be exceeded without careful consideration of the reasons for doing so - - -". In addition, the FRC Report No. 1 states: in paragraph 7.7, " - - - there can be no single permissible or acceptable level of exposure, without regard to the reasons for permitting the exposure."; in paragraph 7.10, "There can, of course, be quite different numerical values for the

Radiation Protection Guide, depending upon the circumstances."⁽⁴⁾.

Thus, the agencies are not rigidly bound to the recommended RPG.

Although the same was true for the NCRP recommendations, flexibility of application was not an obvious trait of the NBS handbook presentations.

In light of the FRC position, the agencies concerned with manned flight operations are clearly free to derive their own radiation exposure limits, that may exceed the RPG, but which meet their own particular requirements.

Evaluation of Hazards

We recommend that the radiation hazards be evaluated from these viewpoints, in order of importance;

- A. Immediate or early (1 week to 1 month) incapacitation at any time during flight.
- B. Progressive incapacitation or serious decrementation of performance over long flight periods.
- C. Delayed or chronic injury as it may require intervention in a planned flight series and as a career limitation factor.

A. Early Incapacitation - This is the emergency or abort dose determination. Depending upon the penetrating quality, total dose, and intensity of the exposure the limiting systemic and/or tissue responses are:

- 1. Acute gastrointestinal or prodromal symptomatology i.e., nausea, vomiting, diarrhea. These may appear within an hour or two and subside within a day at any dose above about 75-100 r at the midline.

2. Acute hematopoietic symptomatology i.e., thrombocytopenia, leukopenia, hemorrhage, intercurrent infection. These symptoms will appear within a few days to a week and can reach a clinically aggravating level at doses of 100-150 r or more to the marrow within several weeks to a month.
3. Widespread erythema and skin blistering. Under certain circumstances, such as extravehicular operations, high intensity surface exposure with little deep tissue dosage may occur. Depending upon the quality of the radiation erythema will appear within a few hours to days following exposures of 500 r to 800 r⁽⁵⁾. Severe damage will occur at doses above 1600-2000 r⁽⁶⁾. Due to the restrictions and abrasive contacts of the space suit, even a partial body moderate erythema could become extremely uncomfortable and somewhat incapacitating.
4. Degradation of general operational skills through direct and indirect physiologic and neurologic injury i.e., lassitude, fatigability. The induction of acute systemic radiation injury is accompanied by nebulous symptoms of reduced performance capacity.

Wherever possible, the above responses should be examined in a probabilistic manner and not all individuals may show the symptoms mentioned above at the stated dose levels. Dose-response relationships should

be derived and upper limit emergency doses defined for the several end points. The lowest limit will be the first determinant, but this will be a function of depth dose variation, total dose, and dose rate. For example, a high dose rate, whole body exposure to a penetrating radiation will undoubtedly cause the dose for prodromal responses to be determinant. A more protracted exposure will bring hematopoietic injury into the determining position, and when moderate to high doses of very low energy radiations prevail under certain unshielded exposure conditions, skin injury will be determinant.

B. Progressive Incapacitation - This response category recognizes that most exposures will be at low levels where no early manifestations will occur, but continued or periodic exposures can lead to a progressive emergence of principally hematopoietic injury expressed as a decrementation of performance necessary to maintain normal flight operations. This category also encompasses one of the most difficult areas for the prediction of biological effect - the situation following fractionated and protracted exposure.

Radiation injury has a comparatively slow time-course of expression and its manifestations will progressively emerge, then subside. Expression and recovery are concurrent. When the exposure is essentially continuous but at a low daily rate - perhaps 2 r/day or less for man - injury and recovery will probably equilibrate and a steady state will be maintained for long periods. Such observations have been made in experimental animal populations⁽⁷⁾ and certainly would occur in man, but there are not yet sufficient data available to establish the kinetics of injury and recovery with any degree of confidence.

One theoretical approach to this problem has led to the evolution of the "equivalent residual dose" (ERD) concept⁽⁸⁾. This assumes a simple linear additive model for injury accumulation and concurrent recovery. The concept will not be discussed at length here, but it should be noted that the assumptions and constants employed in the ERD calculation have never been validated in man and are largely in conflict with much present day radiobiological data. The ERD concept is not based upon a correlation of physiological or cellular injury with lethality, and therefore it cannot determine in any realistic way a dose accumulation that can be related to an acute end point. Nevertheless, the ERD calculation may have some limited usefulness for single doses below 25 r and daily doses below 2 r/day where the level of injury may not, of itself, penalize recovery mechanisms.

At higher daily doses and fractionated exposures, a simple unweighted dose accumulation may be most realistic, since hematopoietic end points will probably be decisive. There are limited data on fractionated exposures in man to support this suggestion. Paired doses of 100 r to 400 r per fraction and at intervals of 3-7 days or two months indicated little or no recovery of the hematopoietic system during the first week and a super-normal sensitivity to second fractions even after the two month interval⁽⁹⁾. These observations are consistent with the Los Alamos accident case that demonstrated a prolonged hematopoietic depression of more than one year⁽¹⁰⁾.

Prediction of man's response is difficult enough when a regular pattern of protracted or fractionated exposure obtains, but when the erratic pattern of exposure that would most likely occur under most

projected flight profiles is acknowledged the situation becomes virtually impossible. The prodromal symptoms and skin lesions will certainly benefit from dose protraction - the unanswered question is: To what extent will the hematopoietic system benefit and what are the significant time factors? We feel this is still largely unknown and emphasize the suggestion that all exposures of 50 r or more per fraction and protractions of 3 r/day or more be measured in terms of a straight exposure dose accumulation when evaluation of acute to subacute hematopoietic injury is under consideration. Small dose fractions of less than 25 r may be managed by allowing for recovery during exposure-free intervals of at least several months duration. No particular recovery constant is recommended except it should be no greater than the 2.5%/day employed in the ERD calculation though it most certainly should be lower if it is to integrate all recovery processes acting over the first several months to a year⁽¹¹⁾.

C. Chronic Injury - As a general point of philosophy, chronic or long-term effects of radiation exposure appear to be of secondary importance in the evaluation of the hazards of manned flight. This should be the case for the foreseeable future, and this point is in sharp contrast to the evaluation of occupational hazards. In the latter, late effects are paramount and among these genetic effects are very influential.

Although the reasons for this relegation of late effects to a secondary role are several, the most quantitative argument is in the matter of population size. The astronaut population may be about 30 to 50; the occupational group may be 200,000 to millions. Chronic

radiation injury is measured in probabilistic and actuarial statistical terms - an increase in an age-cause specific death rate, a reduction of the after-expectation of life, an increase in the sporadic incidence of a detrimental mutation. The end point is not identified with an individual; it is an entity of the population.

Among the different manifestations of chronic radiation injury, genetic damage always receives a little extra attention. This is justifiable for the case of the population-at-large under risk of exposure from fallout radiation or unnecessary medical or dental radiation sources. The gene pool of large populations is sufficient to cause the predictions for even very low probability mutational events to reach values of real concern. However, genetic hazards associated with manned space flight must be considered extremely small. The reasoning is entirely statistical - the small population of astronauts would have a virtually undetectable influence upon the mutational load of the general population. For example, if 50 astronauts receive 200 r apiece in a 10-year flight period, a total of 10^4 man-roentgens will be accumulated. In the same time period, the actively reproducing portion of the U. S. population, about 10^8 persons, are permitted to receive 170 mr/year or 1.7 r in ten years to give a total of 1.7×10^8 man-roentgens. The sum, 170,010,000 man-roentgens, divided by 10^8 is the per capita average exposure level. It is increased by 6 parts in 100,000 as a result of the astronaut exposures. Increases in genetic injury would be proportional.

The logic of the argument is simply that most modern populations are large interbreeding groups and any contribution to the gene pool has a purely random chance of either elimination or transmission to the next generation. Since most new mutations are recessive and only mildly selected against in the heterozygote, they will persist in the population for many generations and thus randomly disseminate from the point of origin.

The above arguments should not be misconstrued as stating that the genetic damage should be of no concern to the individual exposed. Certain probability statements can be made concerning the individual but the acceptance or rejection of these probabilities is somewhat a personal matter.

Non-genetic end points, as the induction of malignant diseases, cataracts, and non-specific life shortening, must also be considered of secondary importance for this small population. Some reasonably acceptable probability statements can be generated for these responses and certainly an awareness of these somatic manifestations of chronic injury must be maintained. It goes without saying that accurate records of the radiation history should be kept on all flight personnel. Since present prediction statements on these effects, in addition to the genetic effects, are always based on the observed total exposure dose, one only requires good record keeping.

It would seem important to be able to freely select from among the experienced personnel those crews that best meet specified mission requirements. This may entail periodic or repeated use of some astronauts

and the possibility of dose build-up to an undesirable level as far as the individual's after-expectations are concerned. Long duration missions may then be jeopardized if critical crew members should begin to develop manifestations of chronic injury when turn-around time may be many months. For this reason, the evaluation of late effects of radiation damage will progressively increase in its importance in the benefit-risk analysis. We feel, however, that these end points should be given very little weight in the present era of experimental manned space flights.

The next logical concern is the question of a "career dose". If we accept this as a necessity, then some value or set of organ-specific values must be established as acceptable "integrated annual dose increments". Are we sufficiently knowledgeable to do this now without being either too restrictive or not restrictive enough? Though one of the authors had previously discussed the matter⁽¹⁰⁾, we now believe it is premature to dwell on the problem of career dosage, if for no other reason than to avoid setting an unrealistic figure for the annual increment. The latter is almost automatically derived when a career dose is established. In this regard, certain existing values for annual incremental dosage derived by manipulation of NCRP recommendations⁽³⁾ provide, in our opinion, unrealistically low values that have no meaning or relationship to the biological effects they are designed to protect against.

One additional uncertainty needs to be noted. This concerns the problem area of combined stress. There is at present, no information

regarding the interaction of weightlessness, radiation and other factors such as the subtle effects that may accrue from prolonged periods of demand for high operating performance. What influence, if any, concurrent physiological and psychological stresses may have upon the expression of radiation damage cannot be ascertained. Since any interaction is liable to influence the response in a negative way, an element of conservatism should be kept in all determinations.

In the meantime, flights will be programmed for longer periods and some limits will be sought for the six months, one year, and two year flights. How should accumulating dose be weighted for prediction of early incapacitation, progressive incapacitation and chronic injury? Some suggestions have been made in this discussion. In recapitulation, for early incapacitation, one will almost invariably be dealing with a single brief exposure and the estimated exposure dose at critical tissue levels will be determinant. For progressive incapacitation, unweighted accumulated dose under certain exposure patterns may be used for hematopoietic end points, with the cutoff being the abort dose. For chronic injury, again a straight forward dose accumulation may be used.

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