THE NEUTRON HAZARD

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Only in the last few years has radiation come to be considered the most likely major cause of casualties from nuclear weapons in a future war. When the first atomic bombs were used against Hiroshima and Nagasaki most casualties were due to mechanical injury and burns, and it is estimated that only 5-15 per cent of fatal cases were due solely to radiation (U.S. Atomic Energy Commission, 1957). Probably as many as 30 per cent had received fatal doses of radiation, but the immediate cause of death was generally injury caused by collapsing buildings, missiles or other secondary factors. Casualties due primarily to radiation were, therefore, a relatively slight proportion of the total, although the novelty of this type of injury attracted wide publicity at the time. Also at that time the nuclear armament was somewhat limited as to size of weapon, and efficient detonations had not been achieved with a yield very different from 20 Kilotons or "Nominal bomb" level. The introduction recently of weapons with very large and very small yield has entirely altered the situation, because both primarily produce a radiation hazard.

The megaton weapon or hydrogen bomb has resulted in the possibility of large areas being affected by radioactive fall-out. This may produce casualties many miles downwind from the explosion and well beyond the range of the blast or heat effects. Relative to these blast or heat effects the effective distance to which ionizing radiation, other than that due to the fall out, extends is small. It goes little beyond the fire ball and can for practical purposes be disregarded. Radiation will be delivered from fall-out remaining on the surface of the ground and undergoing radioactive decay. This may well cause medical problems less familiar to us than acute radiation sickness, though this may also occur. These problems, however, are unlikely to be of importance in a strictly military sense. Although the megaton group of weapons might be used strategically and are the principal civil defence problem, their direct use against armies in the field would seem unlikely except for the purpose of denying ground, because they are really weapons of mass destruction most likely to be used against densely inhabited areas.

There now exists, however, a quite different weapon, recently evolved. This is the small nuclear weapon for a tactical role with a yield in the sub-kiloton range. It can be used on the battlefield by a small group of men, and because of its low yield its effect is felt only up to several hundred yards' radius. The heat and blast effects extend for a shorter distance than the ionizing radiation, and the radiation differs also from that of other nuclear weapons in that neutrons are a more important component than gamma rays. Neutrons, unlike gamma radiation, penetrate dense materials well but are stopped by the nuclei of light elements, such as hydrogen.
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Both the military use and the peculiar biological problems which neutrons present are due to this.

Even where the radiation is from a small weapon the possibility of the radiation dose being largely due to gamma rays cannot be discounted entirely, as shielding might in certain circumstances produce this effect. Very little is known about the effect of neutron radiation from bombs on man, except that comparisons of the incidence of leukemia in Hiroshima and Nagasaki have shown quite marked differences, possibly due to the types of weapons used and differences in their neutron output. On the other hand, a lot of data have now accumulated from experimental work on animals (Vogel et al. 1957).

The Biological Effect of Neutron Radiation

Both neutrons and gamma rays produce ionization within the tissues with consequent release of free radicles. Structural damage to chromosomes and rupture of large protein molecules also occur. The ionization which neutrons produce in tissues are grouped more closely together than ionization due to gamma rays. This higher ionization density of neutrons is perhaps specially damaging to the cells, and may be the reason why to produce an equivalent effect locally a larger dose of gamma radiation is needed. The neutrons also give rise to gamma rays by interaction with the tissues as they lose energy, but only quite a small proportion of the effect of neutrons is due to these rays.

These basic radiobiological differences between gamma rays and neutrons are not the only relevant factors. One major difference in the biological effects of these radiations in the whole organism depends on a purely physical process—their penetration into living tissue. Even neutrons with high initial energies, such as those produced by fission, rapidly give up their energy and penetrate very much smaller distances into the tissues than does hard gamma radiation. This effect of depth does not matter much in an animal as small as the mouse, but in one as large as a man most of the dose will be delivered to the superficial layers and the internal organs will receive much less radiation than they would from an equivalent dosage of gamma rays. In the past most neutron studies have been carried out using mice (Upton et al. 1956) and other small animals (Swift et al. 1958), and the different pathological effects produced have been compared with those of 250 KVP, or Cobalt 60 gamma rays. Quantitatively the ratio of neutron dose to X-ray dose needed to produce the same effect has been known as the relative biological efficiency (R.B.E.) of the radiation. For effects such as the production of sterility (Neary et al. 1957), cataract (Ham, 1953), loss of thymic (Jordan et al. 1956) or testicular weight (Kohn et al. 1954), neutrons have been several times more effective than X-rays, and the R.B.E. has therefore been well above unity. Relative biological efficiencies should, however, ideally be compared only where there is homogeneous irradiation with a pure radiation source. Neither of these conditions is met in a comparison of neutron and gamma radiation effects using fission neutrons. If, on the other hand, one considers large animals, there is little evidence that neutrons are more effective than other types of radiation in producing acute effects (Bond et al. 1956). Furthermore the pathological
effects produced do not always seem to be exactly the same as those produced by X-rays or gamma rays. For these reasons we may choose to compare the results of irradiation of large animals by different radiations by a rather less exact but more meaningful expression known as the potency ratio. "This requires nothing more than expression of the dose to be used in the comparison" (Alpen et al. 1960). In my opinion the dose should be expressed as exposure dose not tissue dose.

It is generally considered that the mid-lethal dose for man (LD50), i.e. the dose that will kill half of those exposed, is about 450 rads for hard X-rays. Bomb neutrons are probably no more effective than this for producing acute lethality in man, i.e. their potency ratio is not more than unity. For other effects, such as the production of cataracts, the figure may, of course, be much higher, as much as ten if the organ is situated near the surface. This is almost certainly a depth dose effect. In my opinion the mathematical comparison of ratios for effects which may be slightly different is not often helpful, and further work on this subject is indicated.

Pathology of Neutron Irradiation

It has been shown that, to damage the gastrointestinal tract of most animals, doses of X-rays in excess of the LD50 must be administered. Severe damage to the gastrointestinal tract results in early death of the animal, occurring perhaps five to eight days after the radiation (Alpen et al. 1958). Should the animal survive this, death results from bone marrow failure and failure of immunity later on, often in the second or third week. Neutron irradiation usually follows this pattern in rodents, in that it produces acute haemorrhagic lesions within the intestinal tract with death in about five or six days. Should the animal survive this, however, it may not die of bone marrow failure but will continue to live, surviving the acute syndrome. Dogs on the other hand which survive the first week may still die from bone marrow failure later (Alpen et al. 1960). There is still insufficient information to know what will be the effect on man.

It has been suggested that as bone has a relatively low hydrogen content, the absorption of neutrons and therefore the energy within it and the adjacent marrow is low compared with that in the soft tissues. Thus even in a homogeneous radiation field the gut would receive a relatively higher dose of irradiation than the haemopoietic tissues (Nowell et al. 1956). To express this quantitatively, it appears that the potency ration for gastrointestinal effects is near 2 for fission neutrons in either rodents or dogs, and for bone marrow effects is likely to be around 0.8 or 1. There is some evidence also that rodents receiving neutron irradiation and surviving the acute stage will develop a high incidence of tumours of the gastrointestinal tract (Nowell et al. 1956), but this has not been confirmed. This would point to some special effect of neutrons on the gut. Observations on the cells of the duodenal epithelium of mice have shown that after neutron radiation there is very much less recovery than after X-rays (Lesher and Vogel, 1958). It appears that neutrons produce a very much larger number of chromosome breaks that cannot be repaired and the cells die. Mitosis is much delayed. This leads to disintegration of the crypts and disorganization of the villi. Where the original crypts have disintegrated, masses
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of chromatin fragments accumulate in the crypt spaces, and where new crypts are slow in forming, the covering of mucous cells sloughs off.

The Military Medical Problem

The medical officer is faced with the problem of treatment of gastrointestinal radiation casualties in the field if small tactical weapons are used in a future conflict. The energetic treatment of these casualties might well be most rewarding, if the radiation dose is predominantly due to neutrons and is not too high, because these casualties may not necessarily suffer bone marrow failure and failure of immunity later. If on the other hand the radiation is predominantly due to gamma rays, such treatment can be of little avail, for a dose high enough to cause the gastrointestinal syndrome is likely to be followed by marrow failure and death.

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