2. Studies of Cancer in Humans

Until the system for estimating the doses received by the survivors of the atomic bombings in Japan was revised in 1986 (DS86), it was reported consistently that the incidence of cancers after exposure to similar doses was higher among the survivors in Hiroshima than among those in Nagasaki (Kato & Schull, 1982). The bomb dropped on Hiroshima was composed of uranium and that dropped on Nagasaki of plutonium, but it was believed that the design of the two weapons had resulted in greater exposure to neutrons in Hiroshima. For many years, differences in cancer rates and in the frequency of chromosomal aberrations in circulating lymphocytes were attributed to differences in the quality of radiation, and attempts to separate the effects of neutrons and γ-rays were made by comparing the rates in Hiroshima with those in Nagasaki (Committee on the Biological Effects of Ionizing Radiations (BEIR I), 1972). On the basis of these calculations, neutrons were estimated to be about 20 times more carcinogenic than γ-radiation, although it was recognized that a wide range of values was possible.

During the early 1980s, the dosimetry of the radiation from the atomic bombs was reassessed (Fry & Sinclair, 1987; Roesch, 1987a,b). The estimated neutron doses delivered to both cities were now considered to be so small (only 1–2% of the total dose in Hiroshima and less in Nagasaki) that estimates of the risks for cancer associated with exposure to neutrons were not reliable (Jablon, 1993; Little, 1997). The change in the estimates of doses to the Japanese atomic bomb survivors thus meant that there was no longer a useful database of human exposures for estimating the carcinogenic risks of exposure to neutrons.

Some workers in the nuclear industry are occasionally exposed to neutrons, but the number of such workers is too small and the doses are generally too low for any meaningful estimate of risk. In addition, these workers were also exposed to higher doses of γ-radiation. In studies of patients treated with neutrons (Catterall *et al.*, 1975, 1977; Hübener *et al.*, 1989; Richard *et al.*, 1989; Kolker *et al.*, 1990; MacDougall *et al.*, 1990; Silbergeld *et al.*, 1991; Stelzer *et al.*, 1991; Laramore *et al.*, 1993; Russell *et al.*, 1993), the numbers of survivors and those developing second cancers are small, and the dosimetry is very complex (Geraci *et al.*, 1982). Other complicating factors include the killing of cells at the high doses used, scattering of low doses and contaminating exposures to γ-rays. High-energy linear accelerators for medical use produce low levels of neutrons through the photonuclear effect, and a dose of the order of 1 cGy is possible (Hall *et al.*, 1995); however, the dose is again too low—in contrast to the dose used for tumour treatment, of the order of 6000 cGy—to allow quantification of the risk for second cancers attributable to neutrons. Epidemiological studies of air crew, pilots and flight attendants have been initiated because of their exposure to neutrons from cosmic rays during frequent high-altitude flights (Blettner *et al.*, 1998; Boice *et al.*, 1999). The annual exposure of air crew is about 1–2 mSv, which, even after a career of 30 years, is still too low a dose to allow detection, much less quantification, of a cancer excess by epidemiological means. In addition, the dosimetry is complex and this population is also exposed directly to ionizing radiation, making it difficult to evaluate the effects of neutrons.