# A dose of the bomb

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**Measurements of high-energy neutron exposure in Hiroshima validate estimates of the amount of radiation that survivors of the atom bomb received. Can we now predict the risks of radiation more reliably?**

On page 539 of this issue, Straume *et al.*[1] present new measurements of the levels of neutron radiation to which survivors of the Hiroshima atomic bomb were exposed 58 years ago. Their calculations resolve a controversy that has existed for two decades — were previous estimates of neutron exposure accurate? It turns out that the answer is yes. But why is this important? We are all exposed to ionizing radiation (X-rays, γ-rays, α-particles and neutrons) — in hospitals and dental surgeries, at home or, in some cases, at work (see Box 1; ref. 2). Health data collected from survivors of the atomic bombs in Hiroshima and Nagasaki are the basis for most estimates of the risks associated with ionizing radiation, which in turn are used to set safe limits for radiation exposure[2–4]. But our ability to estimate risk from this data set is underpinned by our ability to correlate the incidence of disease with the dose of radiation received. If we do not know the radiation dose, we cannot predict the risks.

The atomic bomb, dropped on 6 August 1945, destroyed Hiroshima (Fig. 1). Survivors of the explosion were exposed to two types of radiation: γ-rays and neutrons. There have been several estimates of how much radiation they received, based on interviews with survivors and responses to questionnaires about their location at the time of the bombings. The most recent set of estimates — the so-called DS86 dosimetry system — was introduced in 1986 (ref. 5). But even this dosimetry system was known to be associated with serious problems over the neutron-dose estimates for Hiroshima. Neutron radiation emitted by the atomic bomb consisted of both high-energy 'fast' neutrons and low-energy 'thermal' neutrons — and DS86 predicted that there should have been less low-energy neutron exposure at distances of more than 1,000 metres from the bomb than actual measurements at that distance had indicated[5–7]. Although low-energy neutron radiation represented only a tiny fraction of the total neutron radiation that survivors received, the discrepancy between DS86 and the low-energy neutron measurements had troubling implications for the dosimetry system as a whole. It cast doubt on the accuracy of estimates of radiation levels emitted by the Hiroshima bomb, and also on the calculations of radiation transport through the air[5,8].

Figure 1 **Hiroshima, October 1945. This scene of devastation is the Kamiyacho Road, near the Electric Building, facing west towards the centre of the explosion. (Photo supplied by the Library and Archives Section, Archives Office, Department of Information Technology, RERF.)**

## Box 1 Sources of ionizing radiation

All humans are continually exposed to ionizing radiation, mostly from natural sources. Worldwide, the average human exposure to radiation from natural sources is 2.4 millisieverts (mSv) per year. About half of our exposure comes from the radioactive decay products (mostly α-particles) of radon gas. Most of the remaining natural exposure comes from cosmic rays and terrestrial γ-rays. At ground level, most of the dose from cosmic rays comes from muons, but at aircraft altitudes, neutrons, electrons, positrons, photons and protons provide most of the dose. Dose increases with altitude, so 100 hours of air travel (such as a frequent flyer might travel in one year) would add an extra 0.5 mSv.

Of man-made sources of radiation, most exposure comes from diagnostic medical procedures such as X-rays, and these contribute about 0.4 mSv per year on average. More than 500 atmospheric nuclear explosions, including those at Hiroshima and Nagasaki, took place between 1945 and 1980. Continuing fallout from these gives an annual average dose of around 0.005 mSv. The Chernobyl accident, which occurred in 1986, adds about 0.002 mSv per year on average, and nuclear power production about 0.0002 mSv per year. To put these figures in perspective, the average dose to the colon for the Japanese atomic-bomb survivors was 200 mSv, with the maximum dose in excess of 5,000 mSv (ref. 19). **M.P.L.**

Previous measurements of high-energy neutrons had been unable to verify the accuracy of DS86 at these distances. Until a few years ago, such neutrons could be measured only in sulphur samples. Sulphur measurements made close to the centre of the explosion agreed reasonably well with the DS86 estimations, but there were no useful data more than 1,000 metres from the bomb[5].

Straume *et al.*[1] have now measured high-energy neutron exposure over the distances (900–1,500 metres) where the DS86 estimations differed from the low-energy neutron measurements — the range also relevant to survivor locations. The authors used technology that has been developed to detect trace amounts of the long-lived nickel radioisotope $^{63}$Ni, which is produced from copper atoms by high-energy neutrons. Straume and colleagues have detected informative quantities of $^{63}$Ni in copper samples taken as far away as 1,500 metres from the Hiroshima bomb, and their new calculations of neutron exposure agree with the DS86 estimations over these wide distances.

Closer to the centre of the explosion (around 380 metres), the DS86 estimations may indeed have been wrong. The $^{63}$Ni measurements suggest that actual exposure at this distance was around 35% less than predicted, a finding that is supported by the earlier measurements in the sulphur samples[5]. But because most of the Hiroshima survivors who suffered appreciable exposure were between 900 and 1,700 metres from the explosion[5], this discrepancy is of largely academic concern.

Taken together with previous validations of the estimated γ-ray doses[5], and of the Nagasaki neutron doses[9], it is now clear that the DS86 dose estimates correctly reflect all components of radiation dose in the two cities. So where does this leave the measurements of the low-energy neutrons that initiated these investigations? Embarrassingly, recent re-analyses of these data suggest that if background radiation is taken into account (which the original analyses did not do), then the discrepancy with DS86 largely disappears[10,11].

What are the implications of the new study for risk estimates? One implication is clear: Straume *et al.*[1] have confirmed that neutrons accounted for only 1–2% of the total radiation dose received by the survivors of the atomic bomb (although after accounting for their greater biological effectiveness relative to γ-rays[2], the proportion of the total dose becomes 10–20%), so we cannot derive any useful information about the risks associated with neutron exposure from the Hiroshima bombing[12,13]. But on the positive side, we now have more confidence both in the estimates of the total radiation output from the Hiroshima bomb, and in the calculations of radiation transport through the air. We also have greater confidence in determinations of the relative proportions of γ-ray and neutron radiation to which the survivors were exposed. Will predictions of the risks associated with γ-radiation therefore become more reliable? Arguably yes, but the atomic-bomb data remain contentious as a source of risk estimates for reasons that are largely independent of the dosimetry. Stewart and Kneale[14] maintain that the survivors of the Hiroshima and Nagasaki bombings are highly 'selected', with the degree of selection depending on age as well as the dose of radiation. They argue that such selection invalidates the use of the survivor data for deriving risk estimates that are applicable to a general population.

Is this a real problem? The work of Straume *et al.*[1] and others[5,9] indicates that there are unlikely to be appreciable systematic inaccuracies in the DS86 dose estimates; however, random errors in the dose estimates for individuals still exist. For example, the bomb survivors' recall of their position in the two cities at the times of the bombings was inevitably imprecise. Interestingly, if these random individual errors are taken into account, the selection findings of Stewart and Kneale[14] largely disappear[15]. Moreover, the cancer risks derived from survivor data are statistically consistent with those observed in groups exposed occupationally[16,17] and medically[2,18]. So, despite individual errors, the collective data from the survivors of the atomic bomb are likely to remain a valuable predictor of the risks of ionizing radiation. ■

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**Global change**

# South dials north

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Climate is greatly influenced by ocean circulation in the North Atlantic. But warming episodes, as glacial conditions turned into interglacials, may have been triggered by events far to the south.

The Earth's emergence from the grip of the last ice age took about 10,000 years and was a rough ride. Cycles of rapid warming and cooling preceded a final period of warming, and entry into the current interglacial, from about 10,000 years ago. The dominant player in these events is thought to have been the North Atlantic thermohaline circulation, which transports massive amounts of heat northwards from the tropics, and the effect on that circulation of perturbations in the North Atlantic itself[1]. But might the crucial dials that control this system be elsewhere? On page 532 of this issue, Knorr and Lohmann[2] present a modelling study which shows that slow climate changes in the Southern Ocean around Antarctica (Fig. 1) can influence events in the North Atlantic. Those changes, it seems, may have been ultimately responsible for the abrupt warmings recorded in the Northern Hemisphere.

The Atlantic thermohaline circulation is mainly driven by density differences in bodies of water, density being determined by temperature and salinity. Warm water flows north from the tropics, cooling and sinking as it approaches high latitudes to become a return flow at depth as North Atlantic Deep Water[3]. The traditional view, based on studies of how this 'meridional circulation' can collapse, is that bursts of fresh, less dense water from melting northern ice sheets or background noise in the North Atlantic trigger instabilities that cause it to weaken or shut down[4,5].

Knorr and Lohmann[2] have looked instead at how this circulation can resume after being stalled. They find that, once a threshold is reached, slowly increasing sea surface temperatures around Antarctica and receding sea-ice cover lead to the North Atlantic thermohaline circulation being rapidly switched on. The abrupt increase of meridional heat transport by the ocean causes a sea surface warming of up to 6 °C in the northern North Atlantic within a few decades. These results constitute significant progress in climate studies. They show that slow changes in the south can have abrupt and far-distant consequences, and they link processes operating on scales of thousands of years (such as alterations in Earth's orbital parameters) with the faster changes occurring in, for example, the thermohaline circulation or ice-sheet discharges.

Knorr and Lohmann's climate model is a comparatively simplified one which is efficient for investigating processes associated with deep-ocean circulation and its long