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THE RELEVANCE OF OCCUPATIONAL EPIDEMIOLOGY TO RADIATION PROTECTION STANDARDS

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ABSTRACT

Large-scale epidemiological studies of U.S. Department of Energy workers have been underway since the 1960s. Despite the increasing availability of information about long-term follow-up of badge-monitored nuclear workers, standard-setting bodies continue to rely on the Life Span Study (LSS) of A-bomb survivors as the primary epidemiological basis for making judgments about hazards of low-level radiation. Additionally, faith in the internal and external validity of studies of A-bomb survivors has influenced decisions about the design, analysis, and interpretation of many worker studies. A systematic comparison of the LSS and worker studies in terms of population characteristics, types of radiation exposures, selection factors, and dosimetry errors suggests that the priority given to dose response findings from the LSS is no longer warranted. Evidence from worker studies suggests that excess radiation-related cancer deaths occur at doses below the current occupational limits; low-dose effects have also been seen in studies of childhood cancers in relation to fetal irradiation. These findings should be considered in revising current radiation protection standards.

Environmental and occupational standards are based as much on policy and advocacy as on science; however, scientific studies play a role in justifying standards [1-4]. Studies of cells in vitro and in vivo, animal experiments, and studies of molecular markers of disease may contribute to the scientific evidence. However, epidemiological studies of disease in human populations are especially important in risk estimation and standard-setting because other approaches

necessitate extrapolation from high to low doses, from molecules and cells to organisms, and from other species to humans [5-7].

The ability of external penetrating ionizing radiation (either gamma radiation or X-rays) to cause biological damage was first recognized shortly after the discovery of x-rays in 1896 [8]. A radiation protection standard for workers was first introduced in 1925, and the maximal permissible dose was reduced many times over the next century (Figure 1). The first standards were based on the ability of ionizing radiation to produce acute effects such as erythema (skin reddening) that could be observed immediately in small numbers of exposed persons. However, the appearance of cancers among radiation workers and nuclear physicists showed that radiation could produce neoplastic effects and led to the recognition of the importance of long-term epidemiological studies for understanding radiation risks and setting standards. The current protection standard used by the International Commission on Radiation Protection is 20 mSv whole body annual dose equivalent (Figure 1) [6], however, the United States still permits workers to receive up to 50 mSv per year.

Epidemiological studies have been conducted of medical, environmental, occupational, and military exposures to radiation [5]. Unlike experimental research, these studies lack direct control over measurement and exposure conditions. Radiation doses are often not recorded and may be difficult to estimate; the people included in studies may constitute unusual populations, such as patients with particular diseases, whose relevance to other populations is not clear; and evaluation of many possible outcomes, especially those that are nonfatal, may be difficult or impossible. Furthermore, studies of long-term effects of exposure may suffer from problems of loss to follow-up; and, within a single study population, people with lower and higher doses may differ with respect to confounding factors that affect disease rates even in the absence of radiation exposure. The reliability of the evidence from epidemiological studies therefore depends on their ability to be designed and analyzed to reduce the influence of such biases on the results.

Although workers were exposed to ionizing radiation in various industries prior to World War II, a totally new exposure situation was created in the United States by the Manhattan Project for developing nuclear weapons. Hundreds of thousands of workers were recruited to a new industry situated in remote and secret locations [9]. Because some hazards were recognized in advance, workers at many of these facilities were monitored for radiation exposures, and a new professional discipline, health physics, was created to provide radiological protection (Figure 2) [10, 11]. While the immediate goal of health physicists was worker protection, systematic collection of dosimetry records created an opportunity to investigate relationships between repeated exposure to small doses of radiation and disease that would be relevant to future standard setting.

However, the most influential epidemiological study of ionizing radiation today is not based on follow-up of badge-monitored workers, but on follow-up of

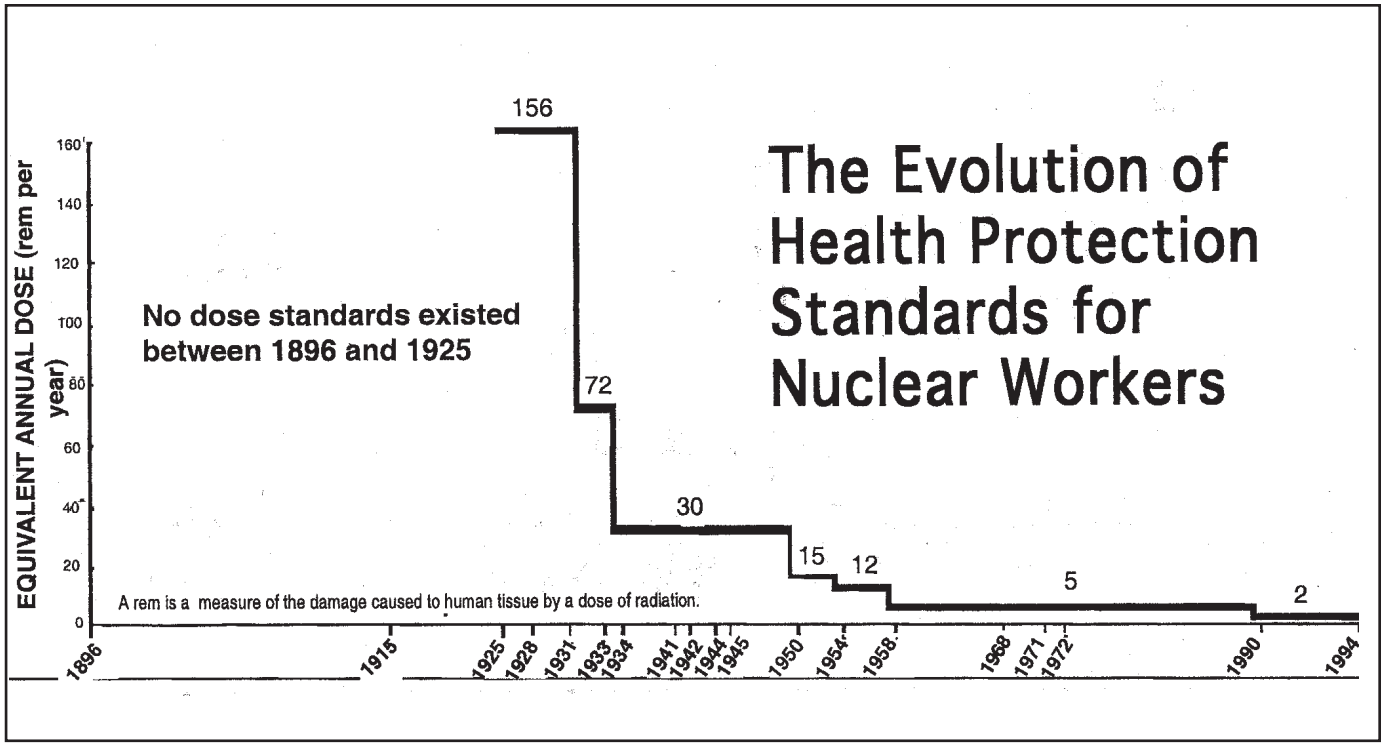

Figure 1. The evolution of health protection standards for nuclear workers. Source: *Closing the Circle on the Splitting of the Atom/The Environmental Legacy of Nuclear Weapons Production in the United States and What the Department of Energy is Doing About It,* U.S. Department of Energy, Office of Environmental Management, January 1995.

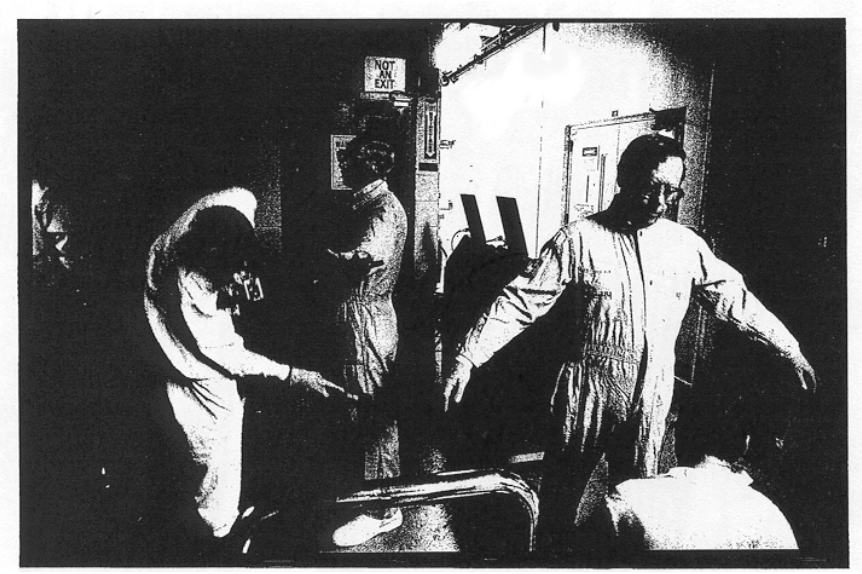

Figure 2. Workers are checked for contamination by radiation at the nuclear weapons plant at Rocky Flats, Colorado. Photo by Robert Del Tredici.

the people who were affected by the bombs produced during the Manhattan project [5]. By the 1960s, when the first large-scale study of nuclear workers was finally initiated more than two decades after occupational dose records began to be collected, many scientific papers and technical reports about Japanese A-bomb survivors had already been written. These reports were widely interpreted as showing that the effects of occupational exposures to radiation would be too small to be detected in epidemiological studies of U.S. nuclear workers [12-14]. However, questions about the reliability of A-bomb findings already had begun to emerge due to the discrepancy between findings of excess risks of childhood cancer following medical irradiation in utero and the absence of an effect among A-bomb survivors who had been exposed in utero [15, 16].

During the last two decades numerous studies of nuclear workers have suggested that radiation risk estimates based on A-bomb survivors could be substantially underestimating the cancer risks from protracted low-level exposure to radiation [4, 17-26]. However, the worker studies have not led to revision of radiation protection standards; rather, the A-bomb survivor study remains the principal source of cancer risk estimates and radiation safety standards, as well as the principal referent for occupational radiation researchers who consider

the A-bomb findings to be a standard for interpreting nuclear worker findings [27-31]. The main purpose of this article is to reappraise the relevance of nuclear worker and A-bomb survivor studies to radiation safety standards. We also review aspects of the scientific climate that may contribute to the dominance of studies of A-bomb survivors, and consider reasons that studies of nuclear workers should receive more attention as a basis for understanding the health effects of repeated exposure to small doses of ionizing radiation.

COMPARISON OF WORKER AND A-BOMB SURVIVORS STUDIES

Japanese doctors began to observe radiation effects even as they were caring for survivors of the nuclear attacks on Hiroshima and Nagasaki [32]. The first major effort to conduct epidemiological studies, however, began during the occupation of Japan by United States forces after World War II when the U.S. government established the Atomic Bomb Casualty Commission (ABCC) under the control of the Supreme Allied Commander. Although Japanese doctors and nurses were necessarily involved in collecting data, the studies were designed and run by scientists from the United States [32], and funding for the successor to ABCC, the Radiation Effects Research Foundation (RERF) continues to come from the United States as well as Japan.

Three types of studies among A-bomb survivors can be distinguished: studies of inherited genetic effects among children whose parents had been exposed to A-bomb radiation; studies of various effects of fetal irradiation; and studies of long-term effects of postnatal exposure to radiation. This last study, called the Life Span Study (LSS), has primarily addressed cancer as an outcome and is the main source of cancer risk coefficients that are widely used to estimate the impact of radiation on cancer among workers and other exposed populations.

The possibility of conducting large-scale epidemiological studies of workers in the nuclear industry was discussed by the Atomic Energy Commission's Advisory Committee for Biology and Medicine in the early 1950s. However, despite the existence of extensive programs to monitor worker exposure to radiation, as well as occupational medicine programs that could have documented biological effects, epidemiological studies were not begun until the 1960s. At that time, Thomas Mancuso of the University of Pittsburgh, a physician who had extensive experience in occupational epidemiology, was asked to direct the U.S. worker studies. Surveys of nuclear workers also have been conducted in other countries (notably the U.K.) and there has been pooling of worker studies from the United States, the United Kingdom, and Canada [22, 29, 30].

When comparing the findings of epidemiological studies, it is not sufficient to consider the results of each study equally; rather, it is critical to evaluate the quality of the study information and how the data were analyzed. Some of the design

issues relevant for consideration when comparing the A-bomb survivor study with studies of nuclear workers are summarized in Table 1.

Study Population

A well-defined study population is relevant to evaluating the generalizability of a study, comparability between exposure groups, and factors related to the susceptibility of a population to the exposure of interest.

Although studies of A-bomb survivors began shortly after the bombings, a list of persons for inclusion in the LSS cohorts was not obtained until after the 1950 census, when individuals were interviewed to collect information about location at the time of the bombing, exposure position, shielding, and acute radiation effects. The people included in subsequent studies have changed many times [33], but in each cohort there have been persons of all ages and a wide range of estimated doses for persons at increasing distances from the hypocenter.

In contrast, studies of nuclear workers in the United States are based on employee rosters taken from primary contractors of the Department of Energy (DOE). In general, prime contractors kept careful records of employees for payroll and security purposes. Epidemiological studies, therefore, begin with an essentially complete list of workers who have ever been employed in a brand

Table 1. Epidemiological Basis for Evaluating External Radiation and Cancer: A-Bomb and Worker Studies

Design Issue	Life Span Study	Worker Studies
Study population	Survivors in 2 cities; all ages	Employee rosters from nuclear facilities; adults
Sample size	75,000-120,000	A few thousand (single facility) to hundreds of thousands (combined facilities)
Exposure	Acute gamma and neutron doses, low to lethal	Chronic low doses, primarily gamma
Exposure measurement	Physical models, survey responses	Individual dosimeters
Outcomes	Cause-specific mortality; cancer incidence; medical surveillance	Cause-specific mortality
Selection factors	Selective survival, chronic effects of acute exposure	Healthy worker effects: – worker selection – worker survival

new industry. As in other occupational studies, worker exposures generally occur between sixteen and seventy years of age.

Sample Size

The LSS study is exceptionally large, and the survivors received a wide range of radiation doses. The cohort with the latest (DS86) dose estimates includes 75,991 survivors, as described in the 1990 report of the National Academy of Science Committee on the Biological Effects of Ionizing Radiation (BEIR V) [5]. Large sample size is a major strength of any survey and contributes to the statistical precision of any radiation risk estimates.

Worker studies vary in size depending upon the number of employees at a facility and eligibility criteria for entry into the study, such as race, gender, date of hire, length of employment, and availability of radiation exposure records. Many DOE worker studies are large, and some of the facilities had tens of thousands of badge-monitored workers on their rosters. Although sometimes workers from several facilities have been combined to increase the study size, this may introduce problems due to differences in the types of exposures, measurements, and selection factors [22, 34].

Exposures

Exposure situations were very different for A-bomb survivors and workers. The whole body exposures of A-bomb survivors came primarily from gamma and neutron radiation emitted during the first microseconds of atomic explosions. Estimated doses ranged from low at long distances from the hypocenter to lethal near ground zero. The high doses of some survivors have been considered a major strength of the A-bomb studies. The RERF studies have ignored doses from irradiated structures and fallout, although Japanese doctors, veterans, and other observers have suggested that these subsidiary exposures might have been important [33, 35, 36]. Fallout that occurred at some distance from the hypocenter of the blasts would be a particular concern for epidemiological studies because it would lead to systematic underestimation of doses for survivors with lower doses from the flash [37].

In contrast, radiation exposures received by nuclear workers occur in research, production of radioactive materials (see photograph), power generation, waste disposal, and assembly of weapons. With the exception of unusual events such as criticality accidents, worker dose rates are too low to produce acute symptoms. The exposure of major interest in many worker populations is cumulative whole body exposure to penetrating ionizing radiation. In facilities that process radionuclides, internal radiation contamination may also be important. Compared to the exposures received by A-bomb survivors, nuclear workers usually receive many small doses spread over a long period of time. It is this pattern of exposure which is of primary concern for radiation protection standards.

Exposure Measurement

Quantification of a relationship between exposure and disease hinges on the ability to differentiate between people with different doses. Studies of the A-bomb survivors began by using distance from ground zero as a surrogate of radiation dose [36], but later methods of dose estimation also took account of shielding and other factors, and major revisions were announced in 1965 (T65 doses) and again in 1986 (DS86 doses). These estimates depend on the quality of two pieces of information: the amount and types of radiation emitted from the bombs, and the location of the person at the time of the bombing. Estimates of the types of radiation emitted came from models of the bombs themselves, from measurements made on test weapons, and from the physical state of the devastated cities. Revised estimates of the relative contribution of neutron and gamma radiation produced by the bombs were the main reason for changes in dose estimates in 1986 [5]. These changes, which led to substantial changes in risk estimates, illustrate the problem of using indirect estimates of dose.

The accuracy of information about the physical location and shielding of each survivor at the time of the blast depended upon the memory of the respondents and the ability of the interviewers to elicit valid information. For A-bomb survivors, problems were introduced by strained relationships between Japanese survivors and the American-run research teams, the effects of a profound disaster on memory, and the social stigma attached to being an "exposed person." Thus, in Japan, eligibility for an arranged marriage could be hampered by concerns about genetic effects of radiation, and some survivors did their best to prevent even their spouses from knowing that they had been exposed [32]. Evidence of acute injuries such as hair loss, erythema, and chromosome damage has been found among survivors whose supposedly low doses could be the result of false reporting of exposure positions [39-40].

Estimates of worker doses are based both on dosimeters incorporated into the security badges worn by nuclear workers (external radiation) and on urine tests (internal radiation). At Hanford and Oak Ridge, annual dose estimates based on the dosimeter readings are available for most of the workers included in epidemiological studies but are sometimes missing for certain years [41, 42]. Furthermore, workers may fail to wear their badges at all times, errors are made in matching hundreds of thousands of dosimetry readings to workers, and changes in dose estimates may occur due to changes in the types of dosimeters used and in the conduct of the dosimetry programs. Despite these problems, the availability of individual physical measurements of radiation exposures for workers is a unique advantage of epidemiological studies in this industry.

Outcomes

The LSS and worker studies have depended primarily upon death certificate data to identify outcomes of special interest, particularly cancers. Despite the

limited medical information available on death certificates, broad categories of cancer are well-recorded, and cancer diagnoses are more accurate than diagnoses for many other causes of death [43]. Additionally, cancer registries in Hiroshima and Nagasaki were used to measure incidence of cancer, including nonfatal cases, and the LSS included medical surveillance of many survivors. Most worker studies have been limited to cause-specific mortality because of lack of reliable information about nonfatal illnesses. Lack of information on nonfatal cancers and nonmalignant diseases limits the ability of epidemiological studies to identify many problems of importance to public health, risk assessment, and standard setting.

Confounding or Selection Factors

The validity of dose response coefficients depends upon the degree to which higher and lower dose groups are similar with respect to other risk factors for the outcome of interest. This may be achieved through design, as in experimental control, or through analysis, as in adjustment for confounding factors.

Most researchers have assumed that A-bomb survivors near ground zero were not systematically different from survivors who were farther away and that, as a consequence, the LSS would be a "natural experiment." However, survival during the five years between the bombings and the beginning of the LSS, a period during which public health infrastructures of medical care, sanitation, water, and food supply were disrupted, would have favored hardy, robust persons. In fact, there is a deficit of higher dose survivors among children and older adults compared to middle ages, which suggests selective survival was most pronounced at the most biologically vulnerable ages [44]. Stewart and Kneale have presented evidence that dose-related selective survival of persons less sensitive to subsequent carcinogenic effects of radiation has led to a downward bias in estimates of radiation risks in the LSS [44-46]. However, continued use of the LSS for cancer risk estimation shows that many scientists continue to believe that "A-bomb survivors, apart from their radiation dose, are representative human beings" [47].

Studies of nuclear workers must also address bias from selection and confounding. Many studies compare cancer rates among nuclear workers to cancer rates among the general population. However, people who are employed (particularly in well-paid jobs that require high levels of education) are, in general, healthier than average, producing a healthy-worker selection effect [48-50]. Furthermore, occupational exposures to radiation are spread over several decades, and, to reach higher dose groups, workers must remain in reasonably good health for many years. Thus, workers who are more prone to get cancer may be less well- represented in higher dose groups because they leave employment or are reassigned to jobs with less exposure, producing a healthy-worker survivor effect [51]. Other differences between more and less heavily exposed workers may be created by assignment of well-trained persons with lower risk profiles to areas

where there are exposures to external radiation as well as other hazards. As in the A-bomb survivor studies, problems of selection and confounding may obscure evidence of relationships between radiation and cancer; however, careful analysis can address many issues of selection and confounding.

Summary

Neither the worker studies nor the A-bomb survivors studies are free of measurement problems and other biases. Nevertheless, studies of A-bomb survivors have continued to play a predominant role in radiation risk estimation despite their focus on an extreme exposure situation, evidence of selective survival, and unresolved questions about inaccuracy of dose estimates. Occupational studies, which investigate low-level exposures similar to those of regulatory concern and have advantages of individual dose measurements, lack of reliance on interviews, and absence of selection related to surviving an atomic attack (Table 1), have been kept in the background.

INFLUENCE OF THE A-BOMB STUDIES ON STUDIES OF NUCLEAR WORKERS

Worker studies have been justified on grounds that they provide a check on the more reliable studies of A-bomb survivors, and assessment of the validity of findings of occupational studies have been based on their agreement with findings from A-bomb studies. This practice is based on the assumption that extrapolating low-dose risk from the studies of high doses is superior to estimating risk at low doses directly because inferences from the A-bomb survivor studies lead to the prediction that worker exposures are usually too low to produce detectable effects [12, 13].

Table 2 presents quotations from the recent occupational epidemiology literature that illustrate these perspectives. The first four quotations, drawn from studies of international, British, and U.S. worker populations, indicate that occupational studies are typically compared to the A-bomb studies as a gold standard [28-30]. They also indicate the role of the LSS in standard-setting. Most importantly, where evidence from worker studies disagrees with studies of the A-bomb survivors, researchers have assumed that worker studies, rather than studies of A-bomb survivors, are in error. This attitude is evident in the second quotation from Gilbert et al. (Table 2). Rather than considering the possibility that the differences in age-related sensitivity to radiation between worker and A-bomb studies might be due to differences in the exposure situations or selective survival among A-bomb survivors, they assume that differences are due to unnamed "biases in the data that are not well understood" [30].

The first quotation from Sever indicates that statistical models chosen for studies of workers are justified on grounds that they were appropriate for A-bomb

Table 2. The Influence of Studies of A-Bomb Survivors on Studies of Nuclear Workers

Citation	Quotation
Cardis et al., 1995	A primary objective of studies of cancer risk among nuclear industry workers is the assessment of the adequacy of existing protection standards . . . based on risk estimates derived from analyses of the mortality of atomic bomb survivors and studies of other high dose exposures.
Kendall et al., 1992	One of the objectives of studies of radiation workers is to obtain direct estimates of risks from exposures to low doses of radiation at low dose rates, for comparison with . . . high dose and high dose rate exposures of the Japanese atomic bomb survivors. . . .
Kendall et al., 1992	The greater dose range and longer follow-up of the Japanese atomic bomb survivors give that study greater statistical power than the National Registry for Radiation Workers.
Gilbert et al., 1993	The analyses expressing risks and confidence limits as multiples of BEIR V predictions (Table VII), which allowed for variations in risk by cancer type, time since exposure, and age at exposure, provide stronger confirmation that risks have not been underestimated by high-dose extrapolation. . . .
Gilbert et al., 1993	If, as seems more likely, the age effects result from biases in the data that are not well-understood, this raises questions about the general validity of using these data for evaluating risks at low doses and dose rates, and certainly suggests caution in interpreting results from studies of nuclear workers.
Sever, 1988	This model was chosen because linear models have commonly been used in quantifying genetic effects due to radiation; in particular, estimates from the Japanese A-bomb survivors are based on a linear model.
Neel, 1994	The genetic data of greatest relevance to the interpretation of the findings of the Gardner-group studies are those collected in the aftermath of the Hiroshima-Nagasaki bombings.
Sever, 1988	Probably the most important consideration in interpreting these results is the contradictory evidence from other studies, particularly the Japanese A-bomb survivor studies.

survivors. Both Neel and Sever, in considering the evidence regarding the potential for occupational radiation exposures of workers to influence cancer among their offspring, considered the contradictory evidence from A-bomb survivor studies to be key to their conclusions that evidence of such a relationship from worker studies should be rejected (Table 2) [27, 31].

Discrepancies between worker studies and A-bomb studies also have been ignored. An increasing number of worker studies suggest both that there is excess risk of cancer at doses well below the current occupational standards, and, contrary to the LSS, that sensitivity to carcinogenic effects of radiation increases with age among adults [22-24, 26]. However, rather than consider the possibility that the LSS is not representative of the original exposed populations, researchers have assumed that worker studies are biased (Table 2).

Stewart and colleagues first questioned the general validity of A-bomb data after observing increases in childhood cancer in relation to in utero exposure to radiation and noting that no similar effects were observed in A-bomb data [52, 53]. Subsequently, risks from in utero exposure were demonstrated in other populations [54, 55]. Although the practice of obstetric radiography was greatly curtailed, this evidence that A-bomb data might be an unreliable source of information about low dose radiation risks was ignored [5]. As in the case of nuclear worker studies (Table 2), a primary reason given by the BEIR V committee for discounting evidence from studies of obstetric radiation was the fact that there was no similar finding among A-bomb survivors.

THE CULTURAL CONTEXT OF RADIATION EPIDEMIOLOGY

Many historians and philosophers of science as well as practicing scientists have noted that the content of scientific knowledge is affected not only by theories and methods of observation and experiment but by cultural forces from both inside and outside the scientific community [4, 8, 56, 57]. The weight given to evidence from the A-bomb survivor studies has some basis in methodological considerations such as the LSS's large size and range of dose variation. However, such considerations cannot explain the deference researchers and policymakers show for this study over other epidemiological investigations, including worker studies, that have important methodological advantages over the A-bomb studies. This situation suggests we must look further for explanations of the dominance of studies of A-bomb survivors in the radiation epidemiology literature.

Almost all nuclear research in the United States has been under the control of the government and large military contractors [37]. Thus, organizations with political and economic interests in promoting nuclear weapons and industrial uses of nuclear technology have also been responsible for research on the health effects of the technology [58]. The climate of secrecy surrounding military research extended into biology and medicine [59]. Recently declassified documents uncovered by the President's Advisory Committee on Human Radiation

Experimentation are indicative of the influence of concerns about liability and public reaction on biomedical research and radiation protection [60]. A 1948 Atomic Energy Commission memo regarding studies suggesting that occupational standards might be too high stated:

> We can see the possibility of a shattering effect on the morale of the employees if they became aware that there was substantial reason to question the standards of safety under which they are working. In the hands of labor unions the results of this study would add substance to demands for extra- hazardous pay . . . knowledge of the results of this study might increase the number of claims of occupational injury due to radiation and place a powerful weapon in the hands of a plaintiff's attorney [60, p. 629].

A 1947 AEC memo from the Oak Ridge Medical Advisor's Office stated:

> Papers referring to levels of soil and water contamination surrounding Atomic Energy Commission installations, idle speculation on the future genetic effects of radiation and papers dealing with potential process hazards to employees are definitely prejudicial to the best interests of the government. Every such release is reflected in an increase in insurance claims, increased difficulty in labor relations and adverse public sentiment [60, pp. 626-627].

These attitudes prevailed during the period when studies of A-bomb survivors were beginning. Early scientific concerns that the studies of survivors might be useless due to problems with data collection and measurement were forgotten as reports appeared showing little evidence of genetic damage from radiation [32]. This was a relief to authorities who were seeking to expand nuclear weapons and power programs. Speculation about an end to the A-bomb studies was replaced by additional funding and an emerging consensus about the importance of studies of this unique population for understanding radiation health effects in humans [32]. Professional careers and a scientific literature were built upon studies of the survivors.

The evolving consensus about radiation risk estimates based on the A-bomb studies suggested, by the early 1960s, that dose response relationships between radiation and cancer would not be detectable in nuclear worker populations. Sterling argued that it was this very consensus which led, in part, to the initiation of worker studies in 1964 [1]. W. M. Schull, a central figure in the A-bomb research, commented on the prospects of occupational epidemiology:

> It seems to be highly probable that if one went through the mechanics of calculating the kinds of radiation effects which a study of the present magnitude might detect, one would be led to conclude that the undertaking is a hopeless one. However, as earlier recognized, it may have other merit in that it may

> provide a firmer basis for settlement of claims against the Atomic Energy Commission [1, p. 40].

S. Marks, who served as Mancuso's project officer for the nuclear worker studies, wrote:

> This study probably will not confirm or refute any important hypothesis but should permit a statement to the effect that a careful study of workers in the industry has disclosed no harmful effects of radiation (if the results are negative as they are likely to be). That statement, supported by appropriate documentation, would seem to justify the existence of the study [1, p. 41].

As a consultant to the AEC, B. MacMahon of Harvard stated:

> In my opinion this study does not have, never did have, and never (in any practical sense) will have, any possibility of contributing to knowledge of radiation effects in man . . . I recognize that much of the motivation for starting this study arose from the "political" need for assurance that AEC employees are not suffering harmful effect [1, p. 40].

This political need was satisfied for over a decade while the effort to assemble worker records on employment, radiation doses, and causes of death proceeded at a pace determined, in part, by low levels of support in comparison to funding for the A-bomb efforts. The first worker study in a scientific journal appeared in 1977, when Mancuso, Stewart, and Kneale reported an association between radiation exposures and cancer death among Hanford workers [17].

Mancuso's contract was terminated in 1978 [61], and responsibility for epidemiological studies of nuclear workers was transferred to groups at Oak Ridge, Los Alamos, and Hanford that had close ties to DOE and the scientific culture built around the A-bomb survivor studies. Gregg Wilkinson, principal investigator of the plutonium worker studies at Los Alamos National Laboratory from 1980-87, wrote that the scientific consensus at DOE was that "exposures were too low to be responsible for the illnesses that were being experienced" by workers [62]. In response to his 1987 report of increased cancer risks among Rocky Flats workers, Wilkinson was admonished by his superiors that he should "write to please the DOE because they provided funding and support" [62]. An independent review of DOE's epidemiology program found that "Secrecy has plagued the entire operation and is totally inappropriate in investigations of health and safety" [58].

Although responsibility for epidemiological studies of nuclear workers was transferred subsequently to the National Institute for Occupational Safety and Health (NIOSH), data-access problems remain and are routinely discussed at NIOSH research and advisory committee meetings. Data access, open scientific inquiry, and adequate funding for worker studies are all clearly important.

However, these are in some ways minor issues in comparison to the problem of the momentum established during a half-century of epidemiological research dominated by studies of A-bomb survivors. Even with open data access and adequate funding, researchers investigating radiation health effects among nuclear workers will have to overcome the constraints imposed by this scientific culture upon hypothesis generation, design, analysis, and interpretation of occupational studies.

CONCLUSION

For more than a half century the study of radiation health effects has been strongly influenced by military and industrial interests. These interests are so deeply woven into the fabric of the scientific culture that scientists participating in the dominant research programs may be unaware of the impact that secrecy, deference to authority, and disdain for concerns of workers and the public has had on the professional culture in which their research takes shape.

We have argued that one reflection of this scientific culture is an increasingly outdated emphasis on evidence about radiation health effects based on studies of A-bomb survivors, a select population whose doses from one-time flash exposures were not measured. Another reflection of this culture is that the A-bomb studies have been used as a lens through which studies of radiation-exposed worker populations are viewed. Thus, despite the unique opportunity to conduct epidemiological studies of low doses and low-dose-rate exposures that have been quantified with individual dosimeters, occupational studies have been viewed as merely a check on findings from A-bomb studies. This view has contributed to delayed attention to studies of worker health, inadequate resources for collection of medical and exposure data, and a failure to fully develop sensitive analytical approaches appropriate for epidemiological studies of workers in their own right.

Scientific attention to nuclear worker studies should increase in the future. Longer follow-up and larger numbers of deaths will increase their statistical power and opportunities for analysis of rare causes of death, disease latency, influences of age at exposure, and other aspects of susceptibility. Greater attention to historical records at DOE facilities should allow better measurement of radiological and other exposures. As researchers and policymakers come to appreciate the unique advantages of studies of nuclear workers, these studies should make a greater impact on occupational and environmental exposure standards.

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