THE HISTORY OF RADIATION PROTECTION

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Man-made radiation was born in physics, its childhood was in medicine, its teenage years in weapons development, and its adulthood at the confluence of all of the peaceful uses of atomic and nuclear energy, where it is today.

Just prior to the beginning of this century, gas-discharge physics was the darling of every experimental physicist. Every high school science and college teacher had a gas-discharge tube, and many of the scientists working with this equipment suggested that there might be radiation associated with the discharge. They knew they could make interesting things happen inside the tube. They weren't quite sure what would happen outside. Lenhart did bring electrons outside the tube through a thin window, but it was Roentgen who decided that some of the radiation could be penetrating the glass. You may know the history. He was adjusting the high voltage on his gas-discharge tube with a fluorescent screen in his hand. As he was adjusting the voltage, he saw the screen fluoresce. He realized that he was observing the results of a penetrating ray, which he called the X ray. He published this observation in less than 30 days (January 1986), and within 30 days of that publication there was the first reported radiation skin burn. So radiation came in with a flurry. Everyone who owned a gas-discharge tube learned that if they got the energy of those rays up high enough, they could make X rays.

By and large, it was the medical community that recognized the enormous potential of the X ray. It was interesting that medicine, at that time, was going through the throes of electrotherapy. Although this practice was being discouraged by the medical community as a whole, the practitioners were still there, and X rays became a marvelous new field for them. The next few years became known as the era of "bullets, bones, and kidney stones." The physicians realized from the beginning that there were potential hazards from radiation exposure. There were ulcers that didn't heal, and there were frequent reports of skin burns, both among the patients and the physicians. It was a long time, however, before anyone thought much about what was causing some of the effects since they had been seen in patients treated in electrotherapy. About 1915, only 15 years after the introduction of the X ray, a physicist named Russ, in England, suggested a set of rules to the British Radiological Society, which they actually printed up on a card, giving advice on avoiding unnecessary exposures. These rules were not very definitive, but at least the Society and, in particular, the authors, understood that there was a problem. However, not much action was taken.

You will note that this advice came to the British Radiological Society. As indicated above, the medical community had adopted this technology, and once a medical association takes ownership of a modality of this kind, they claim exclusivity. In the United States, and pretty much in England and in France, a physicist couldn't publish an article unless he had a physician sponsoring the paper. As a result, most of the literature was related to clinical effects and to clinical use. The situation was different in Germany, where physics and medicine grew up together, and the medical community embraced the physics community. This was primarily because medicine was more heavily regulated in Germany than it had been in these other countries.

Protection advice wasn't heavily organized until, in 1921, that same set of recommendations that had been brought before the British Society in 1915 were now adopted by the British Society as rules that every physician should use. This change occurred because of the development of the hot cathode tube by Coolidge, an engineer at General Electric. This tube was able to produce much higher currents and much higher energies. Many of the radiologists now recognized the tremendous hazard that it posed for them and their patients. In addition, World War I had just taken place, and hundreds of X-ray machines went into the battlefield, mostly with the Coolidge tube. In addition, there were many reports in the public press about anemia, i.e., people ill from blood disease, after the war.

An interesting thing happened at this time that changed the course of radiation measurements. These battlefield machines had to meet military specifications. The Army and Quartermaster Corps was just as difficult then as they are now, which meant that when you went to sell an X-ray machine to the Army, it had to meet a standard, and the National Bureau of Standards provided exactly that. As a result, the physicists involved became a lot more interested in measurement and quantification than had the physicians who had depended upon how red the skin got and whether or not they obtained a good image. Radium had also been discovered shortly after the X ray. The only way you could specify the quantity of radium was through measurement, and at $100 per gram that was very important, so a lot of people were involved in improving the measurement capability in order to make sure that they weren't being cheated. Commerce had its way. Finally, at last, there was measurement of activity.

In 1922, a quantum change occurred. Mutschuler, in the United States, and Sievert, in Sweden, were worrying about the problem of radiation protection. Mutschuler visited a number of well-run clinics in New York City and found that they could operate well without anyone being exposed to more than .01 of an erythema dose in 30 days. This was very important because it provided the first "limit." At the same time, and operating independently, Sievert arrived at a recommendation of .1 erythema dose in a year. Remarkably, they ended up with the same number.

In 1925, the International Commission on Radiation Units (ICRU) was formed as an advisory committee to the International Congress of Radiology at its meeting in Stockholm. Even at the time of formation, the International Society recognized the need to define an exposure quantity. In 1928, the ICRU settled on the amount of ionization in a given quantity of air as the standard, and the Roentgen was defined.

Shortly thereafter, both the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP) made recommendations dealing with exposure levels. The ICRP recommended no more than .2 R/day. It turned out that this is a reasonable measure of about .01 of the erythema dose in thirty days, so that essentially what they had done was to adopt, in a way that could be measured, what Mutschuller and Sievert had recommended three or four years earlier. This means that the first recommendation on dose, although quantifiable, was based on skin reddening. Two years later, in 1934, the NCRP recommended .1 R/day. The ICRP recommendations applied to measurements made at the surface of the body, while the NCRP recommendations applied to measurements made free in air. Measurements made at the surface of the body with the soft X rays would indeed be just about twice what they would be free in air. In fact, the NCRP and the ICRP recommendations were virtually the same.

In the middle 1920s, there were a number of young women working as radium dial painters in New Jersey who tipped their brushes between their lips -- the famous radium dial cases. The physician at that facility came to New York University (NYU) and asked their toxicological group to visit the factory to see if they could help them to understand why there was such serious medical problems such as necrosis of the jaw with these women. The toxicologist who went from NYU, Glump, was very confused because he expected to find red phosphorus, which was a known industrial poison. All he could find was radium. He wrote to Madam Curie and asked if it was possible that radium was doing this. NYU has in its archives a letter from Madam Curie claiming that this fellow was certainly a charlatan, and that radium was for the good of mankind and should not ever be considered to be evil. I don't tell this story to defame Madam Curie. In fact, I will tell another story about her. Madam Curie was a Nobel Laureate by the time of the first World War. In spite of this, she put aside her radium, left her laboratory, and took an X-ray machine into the field to help in the medical service of the soldiers in the war. Half way through the war she came back and taught people how to run X-ray machines. She essentially gave up all her research over the whole wartime period in order to be of service to the soldiers who were wounded.

Eisenbud has made the point, and I will reiterate it here, that it was remarkably fortuitous that, by the late 1930s, the community had at its disposal two recommendations. They had a .1 R/day and they also had a number from the radium dial workers. Robley Evans, from the Massachusetts Institute of Technology, had established that if an individual had no more than a microgram of radium in the bone, it was unlikely to cause damage. The NCRP settled on a recommendation limiting the intake of radionuclides which went to the bone to .1 μgm. Without these numbers, it is hard to imagine what might have happened during the Manhattan Project.

During the war there was a great deal of research in radiation biology going on in places like Oak Ridge, the University of Rochester, Berkeley, the University of Washington, etc., essentially all over the country, to try to get information on the effects of ionizing radiation. Perhaps the most influential radiation protection recommendation at that time was being made by a committee at the Tripartite Conference Meetings. Canada, the United States, and Great Britain set up a framework of radiation protection which they brought to the ICRP and the NCRP in the late 1940s. By the middle 1950s, both the NCRP and ICRP produced new sets of dose limits derived from all the data obtained during World War II.

They recommended 600 mrem per week for the skin, and 300 mrem per week for other organs. I was fascinated to realize that .1 R/day is .6 R/week, which is 600 mrem per week. Essentially, the 600 mrem per week for the skin goes all the way back to .01 of the erythema dose of 1928. The 300 mrem per week limit is more interesting. If you irradiate the whole body with 150 kV X rays, the dose at a depth of 5 cm is just about half of that at the surface. If you were protected by a limit of .1 R/day with soft X rays, the dose to your tissues at 5 cm would be .05 R/day. Now, if we are going to irradiate you with high-energy gamma rays, we should have the same limit for the skin, 600 mrem (.1 R/day) and half of that value for dose at depth 300 mrem (.05 R/day). Again, all based on .01 of the erythema dose per month.

Starting in about 1955, we entered a new era characterized by weapons testing and the public response. There were people all over the world concerned with what was happening. Specifically, there were two individuals who led the scientific community in expressing concern, Mueller, a geneticist, who had been speaking about the linearity of genetic effects even during the late 1930s, and Linus Pauling, who worried about internal dosimetry. As a result of the public concern, the National Academy of Sciences in the United States and the Medical Research Council in the United Kingdom were asked to review the data. Both of these Committees came up with about the same answer. They focused their attention on genetics. They said that it was unlikely that all of man's suffering and pain from genetic abnormalities came from natural radiation background, but that some of it did. Such a consideration bracketed the genetic risk since they knew the natural radiation background levels and the natural incidence of genetic effects. Based on this analysis, both committees came up with an estimate that suggested individuals should not receive more than 50 rem to age 30 and another 50 rem to age 40. I might add that I was able to talk with Eugene Cronkite about this many years ago. Dr. Cronkite was Chairman of the Somatic Committee of the National Academy of Sciences panel at the time of the preparation of the 1956 recommendations. I asked him if the recommendations on exposure limitation came from considerations of the radiologists who had been shown to have an excess incidence of leukemia. He answered that the dosimetry was so uncertain that they could not estimate the dose nor the risk per unit dose associated with leukemia among the radiologists. He noted that what they did decide was that they would accept the genetic panel recommendations, and the Academy recommendations were therefore based almost entirely on the genetic estimates based on a linear extrapolation. Shortly thereafter, Dr. Russell at Oak Ridge showed that there probably was a dose-effect relationship for genetic effects, but it wasn't taken into account.

NCRP and ICRP had to decide the way in which they would recommend that the worker be protected under these new recommendations. As we know, the answer was (age - 18) x 5, which the Nuclear Regulatory Commission discarded just three months ago. The whole body limit was 3 rem/quarter and (age - 18) x 5 and 15 rem/year for individual organs. By the way, 300 mrem/wk for 50 weeks results in 15 rem/year. Again, the critical organ number of 15 rem finds its way back to .01 of the erythema dose in 30 days.

One of the things that I used to say when I talked about this subject in 1977 was that we didn't have a very strong scientific basis for our dose limits. However, by 1977 this situation changed dramatically. This was a result of information that came, not in 1977, but from the period 1960-77 based primarily on data that was becoming available from the Japanese survivors who had been under study from the time of the bomb.

I would like to stop here for a moment because people ought to understand the enormous contribution those survivors and the government of Japan have made in this follow up. I should add that funding for that is now is question by the Department of Energy, and it is incumbent on us all to see if we can help to maintain it.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the National Academy of Sciences, here in the United States, review the data that comes from Japan. They noted that in 1960 the incidence of solid cancer in the Japanese survivors was slightly greater than might have been expected in that population if it had been unirradiated, but excess leukemia was clearly evident. In 1960, they estimated that other cancers are about equal to leukemia. In about 1962, they estimated that other cancers were about two times leukemia, and by 1965 they were suggesting a slightly higher ratio. By the early 1970s, the UNSCEAR suggested that the ratio of solid tumors to leukemia was five or more. What was happening was that the leukemia incidence has a wave effect. The increased incidence starts to show up three of four years after exposure, stays elevated, and drops off. But the solid cancers don't follow that pattern. What we now believe from the data that we have seen in the most recent reviews is that attributable solid cancer occurs at the same ages that you would normally get it if it weren't due to radiation. Therefore, the excess incidence of solid cancer is going to keep increasing. In 1977, UNSCEAR estimated the risk for individual tumors. This was expanded on by the ICRP in its publication 26 in 1977 -- the first scientific approach, I believe, in radiation protection recommendations. The ICRP estimated the total risk to be about 1×10^{-4}/rem. They then compared radiation risks with the risk in safe industries. In safe industries at that time, one person in ten thousand died each year (1×10^{-4}/year) and the ICRP suggested that the radiation workers ought to have at least that level of protection. The ICRP then set a limit of 5 rem/year on the basis that most people who were protected by a limit of 5 rem/year aren't likely to exceed 1 rem/year, and, therefore, the average risk will be the same as that for safe industries. Of particular importance was the concept of a risk-based system. Following this logic, the ICRP provided cancer risk estimates of the more sensitive tissues and suggested that the annual limit on intake (ALI) be based on the specific risk of each tissue. The NCRP caught up with the ICRP recommendations in 1987 (as did the Environmental Protection Agency) and issued its Publication 91.

The recommendations of the ICRP (Publication 60, 1990) are based on further changes. In 1986, a later set of data from Japan became available which suggested two things. First, there is evidence of increased risks based on new dosimetry in Japan and some additional solid cancers. This new data also gave further evidence that cancer from exposure to radiation follows a multiplicative projection model, i.e., attributable cancers will occur at the age they would if there were no exposure, so it isn't until people get to be in their mid-seventies that these cancers are likely to occur. ICRP and NCRP have adopted this new risk projection model. Having such a model is needed to estimate what is going to happen to the Japanese over the next 20 years or so, because, in fact, only about half of them have died up until this point. It is very clear from the Japanese data that exposure to radiation at high dose rates results in excess cancer. You will note I said "high dose rate" since the doses that show these excess cancers are about 100 rem, but 100-200 rem is on the order of the lifetime exposure we might expect for the most highly exposed radiation workers. Therefore, we are talking about an extrapolation from high dose rates to low dose rates, and we must ask the question whether there is time for recovery and repair which might alter our estimate of risks at lower dose rates. ICRP's Task Group on Risk, chaired by Dr. Arthur Upton, suggested you might be able to reduce estimates from very high doses (dose rates) by about a factor of two to get the best estimate in the risk at low doses (low dose rates). The NCRP Committee on Risk, chaired by Michael Fry, suggested the risk at high doses (dose rates) could be reduced by a factor of two to three. What all this means is that we now are on a very firm basis in stating that there is excess cancer in the Japanese. We still have concern about whether we are overestimating the risk by a factor of two or three, or underestimating it by about the same factor. But at least this gives us confidence that we have a fairly firm understanding of the risks that people face. As we apply these risk estimates to deriving dose limits, the ICRP and the NCRP realize the risk estimates had increased by about a factor of four since 1977, when ICRP Publication 26 was published. Since the annual limit was 5 rem in 1977, you might logically divide by four and obtain a new limit of 1 rem/yr. The ICRP did note, however, that the new projection model also changed the most likely age of death from an attributable cancer. That changed from an expectation of death in the middle sixties to expectation of death in the late seventies. In addition, the ICRP felt it was important to base the limit on the risk to the most highly exposed individuals (for whom the limit is needed). Rather than using the safe worker criteria, the Commission felt that it was more appropriate to base their limits on a comparison with an individual worker at the upper end of safe industry risks. This turned out to be about 10^{-3}/year.

This approach is tolerable for the rare individual operating at the dose limit, but it is totally unacceptable to use for any kind of average exposure for individuals who are working in the industry. It is for this reason that ALARA is the essential element in keeping the average exposure far below the dose limit. The dose limits themselves are entirely unsatisfactory as a basis for designing a protection system. The ball is entirely in your court since ALARA is essential in protecting the worker, the public, and the environment.