ONE HUNDRED YEARS OF X RAYS AND RADIOACTIVITY--RADIATION PROTECTION: THEN AND NOW

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It is not particularly remarkable that this topic was one that I chose for an IAEA Symposium which I presented in 1974 (1). My thesis in 1974 was that the basic recommendations and regulations on dose limitation were unchanged from the early 1920s to the date of that lecture. What is remarkable is that during the middle to late 1970s the basis for such recommendations changed to a scientific approach based on risk, and as a result, the recommendations have been under change and modification ever since, although perhaps, as we will see, we may be at a point of some stability once again. I will return to the historical developments, particularly relevant during this Congress when we are celebrating the discovery of the X ray by William Conrad Roentgen just 100 years ago this past November, and the discovery of radioactivity by Becquerel 100 years ago last month. You should also understand that much of this presentation will focus primarily on activities of both the National Council of Radiation Protection and Measurements (NCRP), with particular emphasis on the International Commission on Radiological Protection (ICRP).

Of course, man has evolved in a sea of ionizing radiation. Enhanced exposure to natural radiation took place the first time man moved to a cave where the radon progenies were there for him to inhale. The first occupational exposure that we can trace back in recorded history was to the miners of Joachimsthal and Schneeburg in the 15th and 16th Century Czechoslovakia and Saxony who developed lung cancer from breathing radon progeny while mining for lead (2).

In the middle to late 1850s, gas-discharge physics was a hot topic and the source of wide-ranging experiments in virtually every physics laboratory. These tubes could be found in every high school science laboratory and in any university physics laboratory. On November 8, 1985, Wilhelm Conrad Roentgen was working in his Würzburg laboratory with a Crookes discharge tube. As he was adjusting the high voltage on his gas-discharge tube that he had covered with dark cardboard, he saw his screen of florescent materials lying on the table nearby fluoresce. He realized that he was observing the results of a highly penetrating ray, which he called the X ray. He spent the next two months carefully investigating in detail the properties of this new X ray. During this period, he discovered virtually all of the classical physics properties of the X ray. During these two months he told no one about this discovery except for an anecdotal story which relates that his wife was complaining about his missing meals and being extremely introspective and uncommunicative. Roentgen reportedly took her to his lab where he took an X-ray photograph of her hand -- to her complete astonishment and to his great relief -- he was not, after all, losing his mind! He submitted a paper describing his observations in less than 60 days, during December of 1895 (3). The results of his work were reported in the popular press in Vienna on January 5, and in London and New York by the middle of January 1896. Everyone who owned a gas-discharge tube learned that if they applied high enough voltage they could generate X rays. Thomas Alva Edison was one of the first to see the potential commercial applications of these X rays. For example, in early February, he began a highly publicized attempt to X ray the human brain. Edison had hoped to market an X-ray light bulb, but eventually came to understand the inherent dangers associated with such practices when his assistant, Clarence Dally, died in 1904 as a result of his excessive exposures (4). Dally's death, which was widely reported, had a sobering effect on all of those who were using X rays. In fact, Edison completely stopped working with X rays at this point, although he had already developed a hand-held fluoroscope (5).

When Antoine Henri Becquerel learned of Roentgen's discovery of the X ray using fluorescent materials, he was determined to study these processes in more detail. The material Becquerel chose to work with, fortunately, was a double sulfate of uranium and potassium, which he exposed to sunlight and then placed on photographic plates wrapped in black paper. When developed, the plates revealed an image of the uranium crystals (6). His conclusion was that "The phosphorescent substance in question emits radiation which penetrates paper opaque to the light." He believed that the sun's energy was being absorbed by the uranium which then emitted Roentgen's X rays. However, because the weather was poor on the 26th and 27th of February, Becquerel returned to a desk drawer the uranium-covered plates that he had intended to expose to the sun. On the first of March, when he developed these plates, he expected only very faint images. To his surprise, however, they were clear and strong.

He now realized that the uranium itself was emitting radiation without an external source of energy, and he had discovered radioactivity (7). All by the first of March 1886.

Marie and Pierre Curie, quickly realizing the importance of Becquerel's findings, separated the uranium from pitch blend and eventually found the elements radium (8) and polonium (9), which they laboriously separated from the ore over a period of four years. By 1902, they had a tenth of a gram of radium. During this period, Henri Becquerel had obtained a sample of radioactive material from the Curies, which he placed in a waistcoat pocket. He observed that having worn this waistcoat for less than six hours, he had received a deep burn on his chest (10). He recognized that if this could be destructive to healthy tissue, it should also be destructive to cancerous tissue. As a result of his and the Curies' work, radium followed the same path as X rays in the development of both the medical and nonmedical use of radiation.

By and large, it was the medical community that recognized the enormous potential of the X ray and radium. It was interesting that medicine at that time was dealing with a difficult problem of the use of electrotherapy. Although this practice was being discouraged by the medical community as a whole, the practitioners were still there, and their equipment was ideally suited to the generation of X rays.

During the next few years, medical use of the X ray expanded rapidly, and indeed, this became known as the era of "bullets, bones, and kidney stones." The physicians realized from the beginning that while the medical benefits were unlimited, there were potential hazards from radiation exposure. There were reports in the scientific literature and in the popular press of ulcers that did not heal and scores of skin burns, both among the patients and the physicians (11). The first ulcerating skin lesion was reported by an electrotherapist named Grubbé on January 26, 1886, within a month of the discovery of the X ray (12). By 1915, only 15 years after the introduction of the X ray, both the German Radiological Society and the British Radiological Society had prepared recommendations for physicians on avoiding unnecessary exposure (13). Although these rules were not very definitive, they demonstrated that the societies understood that there was a problem.

As indicated above, the medical community had adopted this technology, and once a medical association takes ownership of a modality of this kind, they tend to protect it as their own. In the United States, and pretty much in England and in France, a physicist could not 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 as its equal. This was primarily because medicine was more heavily regulated in Germany than it had been in these other countries.

Protection advice was not heavily organized until, in 1921, the newly organized X-Ray and Radiation Protection Committee in England presented a set of detailed recommendations as rules that every physician was expected to use (14). The pressure for these recommendations resulted from the development of the hot cathode tube by Coolidge, an engineer at General Electric (15). This tube was able to produce much higher currents and much higher energies. Many of the radiologists now recognized the significant hazard that the use of this equipment posed for them and their patients. Second, World War I had just ended, and hundreds of X-ray machines, mostly with the new Coolidge tube, had been used in the battlefield and were implicated in the many reports in the public press about anemia in the returning soldiers.

It is interesting to note that these military X-ray machines had an enormous impact on the course of radiation measurements as well. The Army Quartermaster Corps wanted to be certain they got what they paid for, i.e., these battlefield machines had to meet military standards. As a result, the National Bureau of Standards was called upon to provide standards, and the physicists involved became more interested in measurement and quantification than had the physicians who had depended upon the redness of skin and whether or not they obtained a good image (16).

Radium commerce also had an impact on measurement. The only way one could specify the quantity of radium was through detailed measurement, which at $100,000 per gram, was very important. Commerce ensured that, at last, there was attention being paid to the measurement of radiation and radioactivity.

In 1922, Mutscheller, in the United States, and Sievert, in Sweden, were concerned about the adequacy of radiation protection. Mutscheller visited a number of well-run clinics in New York City and found that they could operate quite well without anyone being exposed to more than .01 of an erythema dose in 30 days (17). The erythema dose, which is the dose to cause reddening of the skin, had become a common measure of exposure at this time, primarily since there was no generally accepted physical measurement. Nearly every X-ray operator knew how long it would take to develop an erythema at given locations around their X-ray facilities. At the time Mutscheller made this recommendation, Sievert, in Sweden, arrived at a recommendation of .1 erythema dose in a year (18). It is remarkable that these two independent investigators ended up with virtually the same number. Inherent in their recommendation is the concept of a threshold dose. For example, Mutscheller stated, "for in order to be able to calculate the thickness of a protective shield, there must be known the dose which an operator can, for prolonged period of time, tolerate without ultimately suffering injury." Mutscheller's assumption of a "tolerance" level is consistent with the classical threshold response curve so common in toxicological studies. In fact, it is the kind of relationship we see now in most toxicological studies.

In 1925, the International Congress of Radiology at its meeting in London, formed an X-ray unit committee which was to become the International Commission on Radiation Units (ICRU) (19). Even at the time of formation, the international society recognized the need for an internally accepted definition of an exposure quantity. In 1928, the International Congress held in Stockholm adopted a recommendation from this new committee that defined the Roentgen as "the exposure when the X- or gamma- ray field produces 1 e.s.u. of positive charge and 1 e.s.u. of negative charge in 0.00129 grams of air" (20). This definition remained essentially unchanged for 50 years.

At the Stockholm meeting, the International Congress formed the origins of the International Commission on Radiological Protection, the Advisory Group on X-ray and Radium Protection. The U.S. representative to that meeting was Dr. Lauriston S. Taylor, of the National Bureau of Standards. Dr. Taylor was instructed to return to the United States and form a similar organization for the United States so that they could bring a unified position to the future meetings of International Congresses. Taylor returned to the United States and formed the origins of the National Council on Radiation Protection (the U.S. Advisory Committee on X-ray and Radium Safety). Lauriston Taylor was to chair this advisory committee and its successor organizations, the National Committee on Radiation Protection and Measurements and the National Council on Radiation Protection and Measurements, for 49 years until his retirement in 1977.

Shortly after the ICRU provided the definition of the Rontgen, 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 (21). This is a reasonable measure of the exposure that would result in about .01 of the erythema dose in thirty days. What they had done was to adopt, in a way that could be measured, what Mutscheller and Sievert had recommended earlier. This recommendation, although quantifiable, was still based on skin reddening. Three years earlier, in 1931, the NCRP recommended .1 R/day (22). 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 of exposure made at the surface of the body with low energy X rays would indeed be just about twice what they would be free in air. In fact, the NCRP and the ICRP recommendations provided virtually the same level of protection.

Dr. Failla noted, in the 1960 hearings before the U.S. Congress' Joint Committee on Atomic Energy, that he endorsed a limit of .1 R/day based on his observation that two technicians who received that level of exposure showed no observable effects and this limit could thereby be judged to be safe (23).

In the middle 1920s, there were a number of young women working as radium dial painters in New Jersey and elsewhere who tipped their brushes between their lips -- the famous radium dial cases. A New York dentist, Theodore Blum, noted in a three-line footnote to a paper on osteomyelitis of the jaw that he had seen what he termed "radium jaw" in a girl working in a New Jersey dial-painting plant (24).

Much of the early attention to the dial painters came from the National Consumers League, which began under Florence Kelly, and became a virtual crusade (25). By the end of 1926, most of the dial painting intakes had stopped; however, the medical and quasi-medical use of radium and its emanation products were booming. In 1932, a prominent steel executive named Eben Byers, who was a well known amateur golf champion, died of excessive use of a patent medicine, Radithor. Since each one-half bottle contained one microcurie of 226-Radium and one microcurie of 228-Radium, it is not surprising that Mr. Byers' habit of ingesting four bottles per day over an extended period of time resulted in radium poisoning (26). The Los Angeles County Health Department simply could not understand how such a thing could be happening in California, so they went to the California Institute of Technology, where they were put in touch with Robley Evans. This began a long and careful analysis of the effects of radium in bone. By 1941, Evans had studied twenty-seven cases of Radium ingestion, and noted that there were seven cases with residual body burdens below 0.5 micrograms of Radium and no injuries, and 20 with 1.2 to 23 micrograms with various degrees of injury. He presented this data to the Advisory Committee on X-Ray and Radium Protection. Their consensus opinion was that they would accept Dr. Evans' suggestion of .1 microgram (.1 microcuries) of radium as a level "we would feel perfectly confident if our wife or daughter were the subject" (27). This value was published in NBS Handbook 27, March 2, 1941.

Eisenbud has made the point that I will reiterate here, that it was remarkably fortuitous that, before Pearl Harbor and just after the discovery of plutonium, the community had at its disposal two recommendations, an external exposure limit of .1 R/day and body burden limit on internally deposited radium of .1 ug Ra. Without these numbers, it is hard to imagine what the consequences to workers might have been during the Manhattan Project.

During the Second World War there was extensive research in radiation biology going on in places like Oak Ridge, the University of Rochester, the University of California at Berkeley, and the University of Washington, to try to obtain information on the effects of ionizing radiation. Data was obtained on dose and dose rate effects, depth dose, R.B.E.s, radionuclide metabolism, and dosimetry. Perhaps the most influential radiation protection recommendation to come out of this work was that developed by a committee at the Tripartite Conference Meetings held among scientists from Canada, the United States, and Great Britain, countries with access to extensive wartime data (28). They brought their recommendations to the ICRP and the NCRP in the late 1940s. By the middle 1950s, both the NCRP and ICRP had produced new sets of dose limits derived from all the data obtained during World War II (29,30).

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, which means that the 600 mrem per week for the skin is based on the .01 of the erythema dose of 1928. The 300 mrem per week limit is more interesting. If the body is irradiated with 150 kV X rays, the dose at a depth of 5 cm is just about half of that at the surface. If protected by a limit of .1 R/day with soft X rays, the limiting dose to the organs at 5 cm would be .05 R/day. If, however, the body is irradiated with high-energy gamma rays, and the same level of protection is desired as that with 150 Kv X rays, then the limit for the skin must be 600 mrem/wk (.1 R/day) and one half of that value or 300 mrem/wk (0.5 R/day) for the organs taken to be at 5 cm.

Starting in about 1954, we entered a new era characterized by weapons testing and the public response to it. Perhaps one of the most important contributors to the public's fear of radiation can be traced to the worldwide reaction to the fallout from the Bravo Weapons Test on Bikini in March 1954. The subsequent plight of the crew of the Lucky Dragon fishing vessel made headlines, and was coupled in the U.S. with the *Life* magazine cover published on April 29, 1954 depicting, for the first time, a thermonuclear explosion. Now people all over the world became concerned about radioactive fallout. Specifically, there were two individuals in the U.S. 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 exposures. As a result of the public concern about fallout, a National Academy of Sciences Committee on the Biological Effects of Atomic Radiation (BEAR) in the United States and the Medical Research Council (MRC) in the United Kingdom were asked to review the radiobiological data (31,32). Both committees came up with about the same estimate of detriment, having 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 (workers) should not receive more than 50 rem to age 30 and another 50 rem to age 40. (The MRC actually recommended 50 R to age 30 and 200 R lifetime). For the population the BEAR Committee suggested a limit of 10 rem to age 30 for all exposure except natural background. I might add that I was able to discuss this with Eugene Cronkite many years ago. Dr. Cronkite was Chairman of the Hematological Effects Subcommittee of the BEAR Committee at the time of the preparation of the 1956 report. 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.

The NCRP and ICRP had to decide the way in which they would recommend that the worker be protected under these new recommendations (33,34). As we know, the answer was an annual limit of (age - 18) x 5 rem, which delivered 60 rem to age 30, etc. 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 organ limit of 15 rem finds its way back to .01 of the erythema dose in 30 days.

As noted above, my thesis on this subject in 1974 was that there was not a very strong scientific basis for our dose limits. However, this situation changed dramatically by 1977. This was a result of information that came, not in 1977, but from the period 1960-77, and was based primarily on data that was becoming available from the Japanese survivors of the atomic bombing of Hiroshima and Nagasaki who had been under study from the time of the bombs. This study is performed by the Radiation Effects Research Foundation (RERF) under sponsorship by the U.S. Department of Energy (DOE) through the National Academy of Sciences and by the Government of Japan.

I would like to stop here for a moment because everyone should understand the enormous contribution those survivors and the government of Japan have made by their continuing participation in this study. I should add that funding for continuing this important work is now is in question by the U.S. DOE, and it is incumbent on us all to see if we can help to maintain it and to support the absolute necessity for the RERF Directors and Scientific Councillors to set the research agenda.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the National Academy of Science's Biological Effects of Ionizing Radiation (BEIR) Committee review the data that comes from RERF. The UNSCEAR was a product of the same issue that brought about the 1956 NAS BEIR Committee: worldwide fallout from atmospheric nuclear weapons tests. It was created by the United Nations General Assembly in December 1955. The UNSCEAR noted that in 1962 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 that excess leukemia was clearly evident (35), and in 1964, they estimated that other cancers were about equal to leukemia (36). In the early 1970s, they estimated that other cancers were about two times leukemia (37). In 1977, the UNSCEAR provided a fatal leukemia risk estimate of 2×10^{-5} per rem and a total fatal cancer risk estimate of 1×10^{-4} per rem, i.e., the solid tumor risk is about five times the leukemia risk (38).

Based on its own review, the ICRP adopted in 1977 total nominal risk of fatal cancer of about 1×10^{-4}/rem (39). They then compared this radiation risk with the average risk of accidental death in safety industries. In safe industries at that time, one person in ten thousand died each year (1×10^{-4}/year) from accidents, 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 expectation that most people who were protected by a limit of 5 rem/year would be unlikely to exceed 1 rem/year, and, therefore, the average risk fatal cancer will be the same as that for workers in safe industries. In addition, the ICRP suggested that the annual limit on intake (ALI) of radionuclides be based on the specific fatal cancer risk of each tissue results from that intake over the next 50 years. Inherent in the total risk approach is the need to combine internal and external radiation.

The recommendations of the ICRP Publication 60 are based on further changes (40). 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 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 approach their mid-seventies that these cancers are likely to occur. The 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 survivors over the next 40 years or so. The ICRP and the NCRP had both used an additive model prior to 1990. It is very clear from the Japanese survivor data that exposure to radiation at high dose rates results in excess cancer. You will note "high dose rate" since the doses that show these excess cancers are about 1 Sv, but 1-2 Sv 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 of 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) (41). The NCRP Committee on Risk, chaired by Dr. Michael Fry, suggested the risk at high doses (dose rates) could be reduced by a factor of two to three (42). What all this means is that although 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. In fact, the latest data from the former Soviet Union suggest that this reduction factor might be about three (43). As we apply these risk estimates to deriving dose limits, the ICRP and the NCRP recognized that 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, they might logically have been expected to 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. As a result, 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). In this regard, they also noted that the risk of accidental death in industry has been decreasing by ~2% per year. "Safe" industries are now at ~5×10^{-5} rather than 1×10^{-4} yr^{-1}. 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. On this basis, the ICRP recommended a limit of 100 mSv over 5 years and the NCRP recommended a limit based on age in tens of mSv, i.e., if you are 45, you shall not have a cumulative dose >450 mSv (45 rem).

These approaches are tolerable for the rare individual operating at the dose limit, but are totally unacceptable to use for any kind of average exposure for individuals who are working in the industry. It is for this reason that both the NCRP and the ICRP stress that the dose limits themselves are entirely unsatisfactory as a basis for designing a protection system and that optimization should be the focus of our efforts.

The data on exposure to workers and the general public demonstrate the remarkable effectiveness in the application of the optimization philosophy. We can rest assured that the breathtaking advances in medicine and industry can flourish for the benefit of all mankind.

It is only the fear of radiation engendered by incidence the fallout from atmospheric weapons testing (the Lucky Dragon incident), reactor accidents (Three Mile Island, Unit 2), and reactor disasters (Chernobyl) which threaten to derail this remarkable resource. It is essential that those of us in the radiation protection sciences begin to understand public perception and public value so that we can be active and effective participants in public decision-making efforts.

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