BJR

https://doi.org/10.1259/bjr.20200282

Received: 23 March 2020 | Revised: 11 May 2020 | Accepted: 15 May 2020

Cite this article as:
Boice J, Dauer LT, Kase KR, Mettler FA, Vetter RJ. Evolution of radiation protection for medical workers. *Br J Radiol* 2020; **93**: 20200282.

BJR 125TH ANNIVERSARY: REVIEW ARTICLE

Evolution of radiation protection for medical workers

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ABSTRACT

Within a few months of discovery, X-rays were being used worldwide for diagnosis and within a year or two for therapy. It became clear very quickly that while there were immense benefits, there were significant associated hazards, not only for the patients, but also for the operators of the equipment. Simple radiation protection measures were implemented within a decade or two and radiation protection for physicians and other operators has continued to evolve over the last century driven by cycles of widening uses, new technologies, realization of previously unidentified effects, development of recommendations and regulations, along with the rise of related societies and professional organizations. Today, the continue acceleration of medical radiation uses in diagnostic imaging and in therapeutic modalities not imagined at the turn of this century, such as positron emission tomography, calls for constant vigilance and flexibility to provide adequate protection for the growing numbers of medical radiation workers.

INTRODUCTION

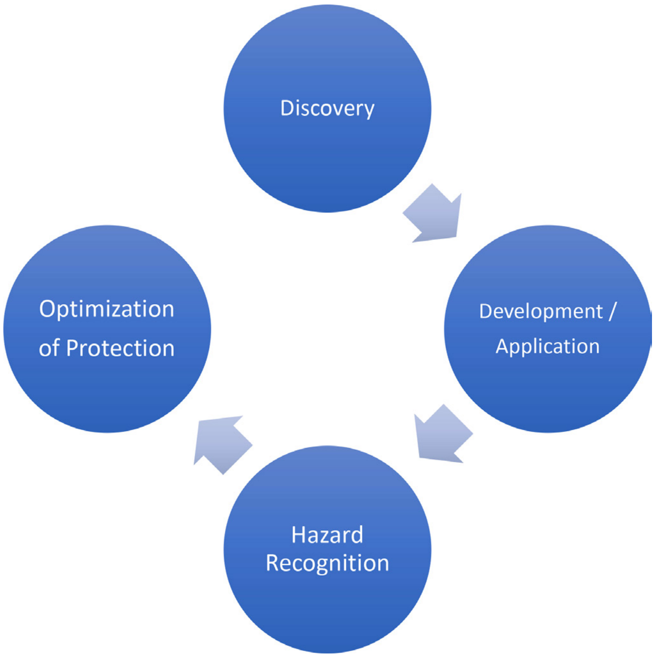
Physicians, nurses, technologists, and others associated with medicine currently comprise the largest single group of workers occupationally exposed to manmade sources of radiation.[1–3] This trend is particularly evident in the areas of interventional radiology/cardiology and nuclear medicine. Medical uses of ionizing radiation have increased substantially over time, especially in the last decade or so, and are especially applicable to rising cancer and cardiovascular disease.[4–6] Historically, the average annual occupational effective dose estimates have trended downward for the medical radiation worker populations (with the likely exception of a leveling through the 1960s) from ~70 mSv prior to 1939 down to ~2 mSv in the late 1970s and below ~1 mSv today, with the exception of physicians who perform fluoroscopically guided interventional procedures.[7] However, for early medical radiation workers, a broad distribution of radiation doses was possible.

The evolution of radiation protection in medicine has historically proceeded in a spiral or cyclical manner through concentrated nodes of scientific activity, including: discovery, development/application, hazard recognition along with the need for control with protective measures, and optimization of protection (Figure 1 Radiation Protection Evolution). A backward glance often informs the present and springboards the future, enabling continuous improvement. Professional societies and various other organizations are essential to ensure adequate training and knowledge dissemination. This review discusses several distinct historical periods addressing selected medical radiation developments, hazard recognition, and associated evolving protection philosophies.

BEFORE THE X-RAY (PRE-1895)

Prior to the initial discovery of X-rays, scientific progression (*i.e.* the standing on the shoulders of giants) included important milestones, such as: Gilbert's understanding of magnetism (1600), Torricelli's vacuums (1643), Newton's electrical machine (1675), Franklin's positives and negatives (1745), Volta's pile (1800), Faraday's electromagnet induction and attempts to explain 'radiant matter' (1850), through to Crook's tubes (1879).[8] With respect to radiation and potential for injury, it was recognized that lung cancers were endemic as far back as the 16th century in European underground metal miners, although clearly not yet linked with any formal conception of radiation, but was later understood to be related to breathing radon gas and its radioactive progeny.[9]

Figure 1. Radiation Protection Evolution



DECADE OF DISCOVERY (1895–1914)

Parallel discoveries of X-rays and radioactive material propelled the world into the previously unknown realm of ionizing radiation. German physicist Wilhelm Konrad Röntgen discovered X-rays in November, 1895.[10,11] The first radiology journal (*Archives of Clinical Skiagraphy* [ultimately to become the *British Journal of Radiology*]) was published in May 1896. French physicist Henri Becquerel discovered penetrating rays emitted from salts of uranium.[12] His discovery prompted Marie and Pierre Curie to separate the substance responsible for emitting the radiation. Madame Curie named this emission "radioactivity" to describe the spontaneous activity.[13,14] The Curies eventually separate enough radium from tons of pitch blende ore to verify its existence as a new element by 1902.[14]

As each of these discoveries progressed, immediate public fascination and interest in the properties of radiation followed, along with recognition that this previously unknown form of energy would have high value in medicine with subsequent widespread and enthusiastic applications (several uncritically) in areas of imaging (coinciding with announcement) and therapy (likely within a few weeks).[15,16] The high level of scientific interest resulted in the 1896 publication of 49 monographs and 1044 special papers on X-rays.[17] Attempts to treat Lupus, ringworm, exuberant growths, tuberculosis, epithelioma, port wine stains, and other maladies were reported early.[18] By 1904, radium became a well-established treatment modality. At the same time, X-ray- and radium-euphoria was rampant in the popular culture. Fascination and commercial interests often resulted in spectacle science with no apparent initial management of associated hazards, and the widespread and unrestrained use of X-rays led to frank injury.[19] Injuries were not initially attributed to X-ray exposure.

The initial uses of and experiments with X-rays and radioactive materials soon resulted in evidence of gross somatic hazard. Some exposures seemed to be desirable (imaging, therapy), but too much might represent an undesirable situation (acute injuries initially). Within barely a month of the discovery of X-rays (1896), Mr. Émil Herman Grubbé (USA) suffered from X-ray burns and dermatitis.[16] In1896, Thomas A. Edison attempted to use the X-ray tube for development of a fluorescent illuminating lamp. He soon abandoned these efforts, however, explaining later"…I started to make a number of these lamps, but I soon found that the x-rays had affected poisonously my assistant, Mr Dally, so that his hair came out and his skin commenced to ulcerate. …I then concluded it would not do, and that it would not be a very popular kind of light, so I dropped it…".[20] In March 1896, Edison reported eye irritation related to the use of X-rays, cautioned against their continuing use, and abandoned further study in his lab.[21] Clarence Madison Dally, his assistant, later developed acute X-ray dermatitis and died of metastatic carcinoma in 1904 at the age of 39, perhaps the first to die as a result of excessive X-ray exposure.[22] Other early experimenters, including William J. Morton and Nikola Tesla also reported independently on eye irritations from X-rays and fluorescent substances.[19]

In 1896, Elihu Thomson, a physicist, deliberately exposed his little finger to the direct beam of an X-ray tube over the period of several days to test the theory that the ray itself was the source of injury. The resulting pain, swelling, and stiffness, led him to caution against over exposure.[23,24]Also in 1896, before attempting to locate a bullet in the head of a child, William-Dudley of Vanderbilt University experimented on himself by exposing his head and noting epilation within 21 d.[25,26] Later that same year, Herbert Hawks, a then recent graduate of Columbia University, gave a demonstration of a powerful X-ray machine in New York and subsequently noted significant dermatitis and related injuries.[27]Becquerel and the Curies later also report on erythemas from carrying small samples of radioactive materials.

The Röntgen Society was formed in 1897 and within the first year setup a Committee "to report on the alleged injurious effects of X rays".[28] This group noted adverse effects including local inflammation of the skin and loss of hair,[29] and agreed in 1898 to collect information on the alleged and various effects of X-rays.[30]

Several protection pioneers developed the earliest guidance and recommendations to prevent injury. As early as December 1896, Wolfram Conrad Fuchs in Chicago recommended X-ray exposures be kept as short as possible, not placing the X-ray tube closer to the body than 30 cm, and rubbing the skin with petrolatum jelly prior to exposure. Others also suggested reduction of exposure time and frequency as the most obvious ways to limit operator exposure, along with filtration of the X-ray beam and the use of collimation.[19] In hindsight, the doses and dose rates from early machines were rather significant (Table 1) and both short-term (*e.g.* dermatitis, skin ulceration, epilation, eye irritation) and longer-term (*e.g.* cataracts, skin carcinomas, and other cancers) adverse biological and clinical effects became evident.[32]

Table 1. Dose rates for radiation workers in the early part of the 20th century (adapted from Inkret et al[31], Table 1)

Occupation	Approximate dose rate ($cGy\ min^{-1}$)
Fluoroscopist	0.5–5 (hands) 0.005–0.05 (body)
X-ray therapy technician	0.005 (body)
Radium therapist or technician	0.005–0.05 (body)

At the turn of the century, William Rollins,[33] a Boston area dentist, performed many investigations into biological injuries by X-rays, including animal studies that noted X-ray injuries were not limited to skin but also appeared at depth within the animals' bodies. Later, he proposed that if 7 min of exposure to X-rays did not fog a photographic plate, then the radiation was not of harmful intensity![33–37] Still, he is considered the premier protection pioneer in the USA[33,37] because he also recommended protective tube housings, the use of leaded glass goggles (1 cm thick), collimated and shielded tubes, shielding for parts of the body not being exposed, the use of pulsed fluoroscopy, as well as selective filtration, all concepts that could be considered forward thinking. He warned of the hazards of ozone and oxides of nitrogen produced by the X-ray apparatus, suggesting means of exhaust and ventilation. By 1904, lead rubber protection for X-ray tubes was available and being employed.[28]

At a 1907 meeting of the American Roentgen Ray Society, as a practical forerunner of personal monitoring, Rome Vernon Wagner, an X-ray tube manufacturer, reported that in an effort to control his personal exposures he carried a photographic plate in his pocket and developed the plate each evening to determine if he had been exposed.[38] Still, by 1911 at least 94 cases of apparent X-ray-induced skin carcinomas and sarcomas were reported, and there was growing concern that exposure to radiation could cause sterility, bone disease, and cancer.[39] At the Brussels Congress of Radiology and Electricity in 1911, there was an effort to define measurements of radiation particularly with regard to the use of radium. Although scientific societies and medical users were beginning to be concerned with the safe use of X-rays, the first professional radiation safety recommendations were not published until 1913 by the German Roentgen society (Deutsche Roentgen-Gesellschaft), a one page warning against cumulative effects of repeated irradiation, together with instructions for providing lead or other such shielding around the X-ray source, the need to stay as far as possible from the X-ray tube when energized, safety testing, and the condition that supporting staff could refuse radiographic work if protection arrangements were unsatisfactory.[40,41] It must be remembered that at this time, there was still no unified and agreed upon system of radiation measurement available for delivery or protection.[42]

WORLD WAR I (1914–1918)

Although X-rays had already been utilized in several battlefield theatres prior to World War I (*e.g.* the war at Sudan-1896, the Graeco-Turkish War-1897, the Tirah campaign-1897, the Spanish-American War-1898, the Second Boers (Afrikaners) War-1899),[43,44] the "War to end all Wars" saw widespread development and application. The use was further precipitated by the 1913 development at the Research Laboratory of the General Electric Company (Schenectady, NY) of the hot-cathode X-ray tube by Coolidge,[45] allowing for stable and reproducible operation[46] and production of large amounts of radiation compared with the earlier gas X-ray tubes.[42] Significant use of radiography in hospitals and on the WWI battlefields with several types of vehicles, dynamos, film processing, and X-ray equipment was quickly created out of urgent need.[36] Marie Curie herself developed more than 200 radiological systems[47] as well as an X-ray vehicle design (voiture radiologique) equipping 18 of them for the French Army.[44] Marie and her daughter Irène Joliot-Curie also opened and operated a school for female X-ray technicians in 1916.[48] Marie died of aplastic anemia in 1934 conceivably related more to her "occupational" exposure to X-rays on the battlefields than to prolonged exposures to pitchblende, radium and polonium.

Following significant exposures of X-ray operators and radiologists during WWI, acute injuries (skin and eyes) as well as cases of leukemia and aplastic anemia were reported in the medical worker population.[28] As of 1913, users understood that standardization in measurement was ultimately necessary and critical. The Röntgen Society therefore initiated a Committee on Röntgen Measurement and Dosage, and a British national radium standard was placed at the National Physical Laboratory.[28] However, the idea of "dose" was still ambiguous and included ideas such as skin color changes, photographic radiometers, electroscopes, Pastille dose, etc.

By the turn of the century, faster photographic plates and improved techniques were available that assisted in reducing some of the acute hazards.[46] Advocates for protection remained vigilant in the face of overwhelming evidence of the potential for injury. Heinrich Albers-Schönberg (himself an early victim of chronic X-ray dermatitis) suggested restrictions on exposure frequency (no more than 3 times a day), a distance of 30 cm from the tube to the patient, a leaded tube housing, and additional lead shielding for the operator.[46] Note that this may be the earliest delineation of the basic radiation safety principles of time, distance, and shielding. There were even early calls by the news media for state licensing of radiographers.[49]

In 1915, the British Röntgen Society, recognizing the plight of the radiologists who operated often primitive unshielded equipment,[50] passed a resolution proposed by Mr Cecil R. C. Lyster "that the safety of operators should be secured by universal adoption of strict rules, and that the Society should take steps to ensure this." Later that year, the Society produced recommendations for the protection of X-ray operators,[28,51] a code of practice that noted the harmful effects produced by X-rays (cumulative and latent), importance of qualified medical practitioners, shielding and collimation, avoidance of operator exposures (protected spaces), not holding anything in the beam, shielded X-ray tubes, and tests of available shielding. Such guidance signified an active organizational interest in X-ray protection. Rules at the time included and emphasized electrical hazards (significant in those days), ventilation (perhaps from ozone production from primitive equipment at that time), limited work hours, and recommended extra vacation for radiation workers. In 1917, the British Association for the Advancement of Radiology and Physiotherapy (BARP) was formed which became the British Institute of Radiology in 1924.

INTERWAR PERIOD (1919–1938)

During the interwar period, national and international collaborations became important and advanced the protection of workers. The American Roentgen Ray Society established the first standing committee on X-ray protection in 1920 and they adopted radiation protection recommendations similar to the 1915 British Roentgen Society.[19] The British X-ray and Radium Protection Committee[52,53] updated its recommendations for radiation safety in 1921, importantly addressing staff safety, the expanding role of radium in medical therapy. The recommendations to protect X-ray operators included maximum work schedules, required amounts of leisure time, and special accommodations for the workers. Radiographers/radiologic technologists and radiologists began to be recognized as discrete professions. The Society of Radiographers in the UK and the American Society for Radiologic Technology were both founded in 1920 and the American Registry of X-ray technologists gave the first certification examination in 1922. The American College of Radiology was founded in 1923.

The First International Congress of Radiology held in 1925 at Westminster, established an X-ray Unit Committee which was requested to setup an International Committee on X-ray Units (eventually becoming the International Commission on Radiological Units – ICRU).[42] ICRU importantly proposed quantities and units of radiation and radioactivity, recommended measurement procedures and provided physical data necessary for application,[54] and in 1926, an X-ray laboratory was established at the US National Bureau of Standards.[42]

During this period, important advances in individual monitoring took place. Edith Hinkley Quimby, a New York radiological physicist, applied herself to developing appropriate safe-handling techniques for radioactive material.[55] She devised a highly practical film dosimeter that incorporated metal filters to minimize energy dependence of the film during routine use of film badges and standardization of interpretation.[56] Robert Landauer, Sr., similarly recommended the use of easily obtainable dental film packets for monitoring purposes.[57]

In an ongoing collaborative manner, the Second International Congress of Radiology setup the International X-ray and Radiation Protection Committee (IXRPC) in 1928 (later becoming the International Commission on Radiological Protection (ICRP)).[42] Perhaps as important, participants designated the roentgen (R) as a unit for measuring radiation. This finally provided a physical basis for quantitative measurement, permitting documentation of standardized radiation exposures. Development of ionization chambers (*e.g.* Victoreen) and other survey devices soon followed.[37] The concepts of dose and measurement were originally elaborated by William Lawrence Bragg,[58] and later expanded by Louis Harold Gray.[59,60]

In 1929, Lauriston S. Taylor, the only US member of the IXRPC, after consultation with the presidents of several US radiological societies (Radiological Society of North America, the American Roentgen Ray Society, and the American Radium Society), established a single group in the USA called the Advisory Committee on X-ray and Radium Protection. This committee wrote recommendations for radiation protection which were published by the National Bureau of Standards.[42] Eventually, this organization would become the National Committee on Radiation Protection and subsequently be Congressionally chartered in 1964, but remain independent, as the National Council on Radiation Protection and Measurements (NCRP).

Many latent effects from the war time use of X-rays began to appear in the early 1920s and by the mid-1920s, the concern of radiologists over their own radiation injuries was at a near panic level. Professional societies began to take more serious interest in pragmatic protection practices, or in limiting medical use altogether.[42] Other potential risks were also beginning to be recognized. Hermann Joseph Muller's experiments[61,62] demonstrated that exposure to X-rays appeared to cause genetic mutations in fruit flies (Drosophila). By the late 1920s, the plight of the "Radium Girls" was taken up by the general media, pointing to significant medical impacts on young workers who dipped paint brushes into radium paint and sharpened the bristles with their mouths, some ingesting significant quantities of radium which accumulated in their bodies and markedly increased the occurrence of osteosarcomas and carcinomas of the mastoid cells, aplastic anemia, leukemia, bone fracture, and radium jaw.[19,63–66]

An understanding of radiation biology and dosimetry was severely inadequate during this period. Although lacking measurement techniques (*e.g.* there were essentially no instruments of a clinical nature that could measure the relatively low levels of scattered radiation to determine shielding adequacy) and with only an elementary understanding of radiobiology (mostly skin erythema[67]), certain precautions were prescribed. Based on available information at the time, it was determined that the threshold erythema dose (TED) causing initial observable injury was equivalent to about 650 R under typical conditions.

Initially, on the basis of finding no evidence of injury to a few hospital X-ray technicians who were working in radiation fields up to as much as 0.1 TED per month, an acceptable value of 0.01 TED per month was proposed. In a step of prudence, however, in 1921, the British developed the first formal attempt at operator dose restriction, setting a tolerance dose of X-rays, equivalent to 1/10 of the erythema dose per year (about 65 R, or roughly ~1R per week, or 500 mSv per year).[53] At that time, the safety emphasis still included limiting working hours, large rooms, well-ventilated spaces, above-ground suites, proper shielding, 6 weeks of vacation, and periodic blood tests. Several countries (*e.g.* USA, Sweden, Italy, France, and Germany) adopted this initial pattern of protection.[42] Many of these early recommendations also included emphasis on electrical shock and artificial resuscitation, because electrocution was a real and present danger even in hospitals (X-ray rooms were typically laden with open high voltage lines).

In 1924 at the American Roentgen Ray society meeting, Arthur Mutscheller recommended the use of a tolerance dose (considered to be that level of radiation to which an individual could be continuously exposed without demonstrable ill health effect or harm) approach for protection based on 1/100 of the quantity known to produce a skin erythema per month (equivalent to about 0.2 R per day), noting at this exposure level recovery would happen swiftly with no apparent injury.[19] Others, including Alfred Ernest Barclay and Sydney F. Cox as well as Rolf Sievert also put forth tolerance dose concepts at that time.[37] Recommendations also considered the hazards of toxic chemicals from burning X-ray film as well as protective measures for both patients and those occupationally exposed. With regard to radioactive material precautions for workers, George Miller MacKee[68] decried in 1927 that improvements in X-ray and radium protection were still needed, noting that "[t]here is really no excuse for injury to a physician by radium", and suggesting the use of caution signs, distance, tongs, shielded containers, as well as surveying for loose sources.

The IXRPC recommended tolerance dose in 1934 as an upper limit for exposure of workers[69,70] and the fourth International Congress on Radiology set a quantitative permissible dose level of 0.2 R per day for those in normal health (1 R per week).[70] By this time, the US Advisory Committee had already adopted a lower 0.1 R per day for the whole body and 5 R per day to the fingers, as suggested in 1932 by Gioacchino (Gino) Failla (noted physicist and pioneer of the use of gold-filtered radon implants at Memorial Hospital in New York).[55,71] Additional recommendations included pre-employment physicals, 6 weeks of vacation, and periodic blood counts. To insure the dose limits were not exceeded, a typical industrial safety factor of 10 was applied, resulting in a general working standard of about 0.01 R/day.[42] By the end of the 1930s basic exposure limits, recommendations for X-ray protection, and some for radium protection were in place. However, war had again caught up with the world and several professional committees went into an inactive state until the fall of 1945.

WORLD WAR II (1939–1945)

The protection concerns surrounding the development of the atomic bomb during World War II added new dimensions, both qualitatively and quantitatively to occupational radiation protection.[50] For obvious reasons, this era saw the development of radiation protection (health physics) as a science in its own right.[72] The Manhattan Engineering District project development of the atomic bomb and the associated development of Health Physics produced enormous advances in radiation protection, survey instruments, monitoring techniques, and radiobiological research, all under war-time secrecy.[73,74] The previously recommended limit of 0.1 R per day[71] formed the basis of initial protection recommendations as the first nuclear reactor operated in Chicago (1942), the uranium enrichment and plutonium production facilities were developed in Tennessee and Washington, and the initial atomic bomb was developed and tested in New Mexico (1945).[75] The use of nuclear weapons led to the first long-term epidemiologic studies that would profoundly influence radiation protection concepts, recommendations and regulations for the next 70 years.

The potential for medical worker radiation exposure expanded significantly with development of high voltage X-ray production devices (*e.g.* betatrons, linear accelerators) and reactor-produced high activity radioactive isotopes available for therapeutic uses. With recognition of ingestion hazards (especially evident with radium), the 1941 NBS Handbook H27[76] reaffirmed the recommended limit of 0.1 R/day for external exposure of radiation workers, and set a maximum permissible body burden of 0.1 μCi for ingested radium. This first internal dose standard was set to be lower than the amount of radium remaining in any of the luminous radium dial painters who had suffered from bone cancer as noted in the pioneering work of Robley D. Evans.[19,65,66] A maximum permissible airborne concentration equivalent to 10 picocurie of radon per liter was recommended to limit radionuclides in the workroom atmosphere.

In 1944, Edith Quimby elaborated a radiation protection philosophy for workers and argued the importance of setting some sort of "permissible dose" on the basis of calculated risk – a balance of known good against the possibility of harm – and then to establish procedures to make sure that no individual received more radiation than this permitted dose.[77] A working check list for a safety program that she developed during this period included important (still quite relevant today) considerations, such as: why is radiation being used at this time? (justification); Who is being exposed? (any special precautions required); What part of the body is being exposed? (sensitive organs and scatter are important); Is the apparatus employed the best for the purpose? and Has the entire examination been carefully planned to give the minimum total exposure? (an early aim of optimization).

POST WAR (1946–1960)

Following the war, new considerations for radiation protection were provided by the release of much of the information generated from the wartime research. These included concepts of absorbed dose, dose-equivalent, and relative biological effectiveness, amongst the explosion of ideas and approaches. The addition of new machines along with new diagnostic and therapeutic modalities, including nuclear medicine applications as Manhattan Project reactor-produced isotopes were beginning to be distributed to civilian researchers, required expansion of the profession of health physics (radiation protection).[50] Important standardization was necessary and forthcoming from professional societies. In fact, the NCRP, many of whose members had worked with radiation during the war efforts, produced about a dozen detailed reports during this critical period[75] with the ICRP soon following. Topics include whole body exposure, critical organs, neutron exposure, internal exposures, and the need for a standard or reference human for modeling dose distribution in the body.

Table 2. Chronology of external whole-body occupational radiation protection standards

Year	Recommending organization	Criteria	Reference
<1934	-	~100 rem	
1934	IXRPC	0.2 R/d (60 rem/y)	International X-ray and Radium Protection Commission[70]
1934	NCRP	30 rem/y at 0.1 rem/d	NBS Handbook 18
1937	IXRPC	0.2 R/d (60 rem/y) 1 R/wk	International X-ray and Radium Protection Commission[78]
1950	ICRP	15 rem/y at 0.3 rem/wk	NBS Handbook 47[79]
1954	NCRP	3 rad/13 wk 0.3 rad/wk max 15 rem/y	NBS Handbook 59[80]
1958	NCRP	3 rad/13 wk 0.3 rad/wk max 15 rem/y 5(N-18) rem accumulated	NBS Handbook 59 addendum[81]
1958	ICRP	0.1 rem/wk three rem/13 wk 5 (N-18) rem accumulated	ICRP Publication 1[82]
1965	ICRP	3 rem/13 wk 5 rem/y max	ICRP Publication 9[83]
1971	NCRP	3 rem/13 wk 5 rem/y	NCRP Report 39[84]
1977	ICRP	5 rem/y acceptable risk	ICRP Publication 26[85]
1987	NCRP	50 mSv/y 10 mSv x age (y) cumulative 150 mSv/y (lens of eye) 500 mSv/y (other organs, extremities)	NCRP Report 91[86]
1990	ICRP	20 mSv/y avg over 5 y 50 mSv in any single y 150 mSv/y (lens of eye) 500 mSv/y (other organs, extremities)	ICRP Publication 60[87]
1993	NCRP	50 mSv/y 10 mSv x age (y) cumulative 150 mSv/y (lens of eye) 500 mSv/y (other organs, extremities)	NCRP Report 116[88]
2007 2011	ICRP ICRP	20 mSv/y avg over 5 y 50 mSv in any single y 150 mSv/y (lens of eye) 500 mSv/y (other organs, extremities) 20 mSv/y avg over 5 y (lens of eye) 50 mSv in any single y (lens of eye)	ICRP Publication 103[89] ICRP Publication 118[90]
2018	NCRP	50 mSv/y 10 mSv x age (y) cumulative 50 mGy/y (lens of eye)	NCRP Report 180[91]

In 1948, the British X-ray Radium Protection Committee suggested maximum permissible dose (MPD) of 0.5 R per week and, during fluoroscopic continuous exposures, and maintained less than 4-6 R per second. In 1950, the ICRP lowered its recommended MPD from 0.2 R/d to 0.3 R/week (Table 2)[79] and included recommendations for maximum permissible concentrations in the body for about 10 radioactive isotopes.[92] Similarly in 1953, the NCRP expanded the recommendations on maximum permissible amounts in the human body to include dozens of additional radioisotopes.

In an important worker-protection development, the NCRP[80,81] accepted the use of absorbed dose rather than exposure as a preferred way to express protection limits. In addition, NCRP noted that there might be some degree of risk at any level of exposure and the risk to the individual is not precisely determinable.

NCRP stated that however small the risk, it is believed not to be zero, leading to the recommendation "exposure to radiation should be kept at the lowest practicable level in all cases" (later revised by ICRP to "as low as reasonably practicable" and eventually to "as low as reasonably achievable," the ALARA principle).

Although radium implants had been used for decades, by the early 1950s the hazards to operators, surgical theater staff and others was recognized as a very serious problem and brachytherapy experienced a marked decline. In 1956, Keith Mowatt and Keith Stevens[93] described the technique of afterloading that markedly reduced operator's doses. In 1960, Ulrich Henschke described intracavitary afterloading for cervical cancer.[94] Other reductions in operator dose were realized in X-ray fluoroscopy procedures as older fluoroscopes (requiring dark adaptation and close distances for the physician) were replaced with image intensifiers and television viewing.[95]

While some radioactive isotopes were able to be synthesized prior to the war using cyclotrons (*e.g.* ^{130}I and ^{131}I in small amounts), after World War II, it became possible to create large amounts of radioactive elements in nuclear reactors. These new isotopes (*e.g.* ^{32}P, ^{60}Co, ^{137}Cs, ^{125}I, ^{103}Pd, and many others) were much safer to handle and administer than radium or radon seeds and were employed for therapeutic purposes, also effectively reducing staff exposures.[2] For example, in the late 1950s chromic phosphate (^{32}P) was substituted for gold (^{198}Au) colloid which had caused higher absorbed doses to nursing staff and other hospital patients.[96] While a revolution in imaging and treating thyroid cancer was enabled by the more general availability of ^{131}I, the development of Tc-99m generators and "kits"[97] revolutionized medical imaging. These also introduced new exposure scenarios for medical staff.

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) was established in 1955 to assess levels and effects of exposure to ionizing radiation and to report those to the United Nations (UN) General Assembly. The 1958 UNSCEAR Report noted the principal sources of radiation exposure to humans were natural background and medical radiology.[98] In 1957, the International Atomic Energy Agency (IAEA), an autonomous UN organization, was formed in response to an earlier "Atoms for Peace Speech", an address by US President Dwight Eisenhower to the UN General Assembly, seeking to promote the peaceful uses of atomic energy.[99] The IAEA continues to base its advice on recommendations of ICRP, typically in a manner suitable for direct inclusion in national legal standards.

National and international efforts for standardizing protection continued and in 1956, the British Medical Research Council recommended a lifetime limit of 200 R whole body and 50 R for gonads.[100] Soon after, the NCRP and ICRP recommended an annual occupational dose limit of 5 rem per year,[81] and in 1958, the NCRP recommended, for accumulated dose to a radiation worker, the maximum permissible dose (MPD) to the most critical organs, accumulated at any age shall not exceed 5 rem multiplied by the number of years beyond age 18, and the dose in any 13 consecutive weeks shall not exceed 3 rem.[75] Similarly, in 1958, the ICRP recommended limiting occupational exposures to 0.1 rem/wk, 3 rem/13 wk and 5(N-18) rem accumulated working lifetime dose.[82]

By the mid- to late 1960's, UNSCEAR noted that the most significant stochastic effect was cancer and not hereditary issues as had been previously assumed and this changed emphasis in radiation protection.[101,102] Further, epidemiologic studies were revealing radiation-related increased cancers at lower doses than previously seen, and evidence for dose–response relationships for leukemia and solid cancers was emerging. Investigations of the early radiologists and medical practitioners in the United Kingdom, USA, China and Japan confirmed that occupational exposures to relatively low dose radiation over a period of many years did cause detectable increases in leukemia.[101,103,104]

This era saw the maturation and branching of radiology into several specialties (diagnostic radiology, nuclear medicine and radiation therapy) each with their own radiation protection issues. This happened not only for physicians but for technologists as well. In 1958, the European Union of Medical Specialists was formed, which would later lead to a number of discrete certifying boards with radiation protection included as required material. The Royal College of Radiology was founded in 1975. Relevant professional societies (including the American, European and other national societies for radiology, radiation oncology and nuclear medicine) played important roles in both developing and communicating information about radiation protection to their practitioners.

1970S TO 1990S – EARLY MODERN ERA

The 1970s through 1990s, or early modern era, saw immense growth and complexity in the medical applications of radiation and radioactive material.[105] CT was invented in 1972 at the British EMI laboratories by Godfrey Hounsfield and Allan Cormack[106–108] and had a great impact on medical imaging, especially with the introduction of fast and multislice systems as computing power increased. The doses to operators were markedly reduced compared with other imaging methods such as fluoroscopy; however, patient doses were significantly higher than for standard screen-film X-ray procedures.[109] This era also saw the development of positron emission tomography (PET) scanning techniques[110] with concomitant rise in nuclear medicine staff doses.[4,111–114] By the mid-1970s the majority of diagnostic tests carried out in nuclear medicine departments made use of ^{99m}Tc-labelled radiopharmaceuticals which compared to other radionuclides resulted in lower doses to technologists.[115,116] Fluoroscopically guided interventional procedures began to increase in the late 1980s. By the early 1990s, reports of fluoroscopically induced skin injuries reappeared in the literature after an absence of more than 50 years.[117,118]

Protection of staff and patients improved with the use of personal protective equipment (*e.g.* lead aprons and thyroid collar shields),[7,119] developments in the accuracy and quality of radiation instrumentation, radiation dosimetry and improvements in imaging and equipment design and operation.[120–122]

Development of tissue-equivalent phantoms during this period allowed more accurate estimates of radiation dose in human tissue. Better understanding of patient dose related to specific procedures resulted in improved control of patient doses.[123,124] Dose delivered to the breast during mammography had been a concern since the beginning of the use of this technology for screening for breast cancer. Dose control was significantly improved by a better understanding of dosimetry for low-energy X-rays and the introduction of quality assurance procedures.[125–127]

In its 1977 recommendations for radiation protection, ICRP expressed the need to take precautions when assessing the benefit and necessity of performing a procedure that would result in radiation exposure to a developing fetus. "Because of the risk of radiation injury to any embryo or fetus, the possibility of pregnancy is one of the factors to be considered in deciding whether to make a radiological examination involving the lower abdomen in a female of reproductive capacity."[128] However, at this time no specific recommendation was made for restricting radiation dose to the fetus. Recommendations for limiting the fetal radiation dose later appeared in ICRP Publication 60.[85]

The important topic of effective facility design to reduce radiation exposure of medical staff was addressed in reports issued by the NCRP published in 1976 and 1977,[87,129,130] these reports provided data on radiation interactions with various possible shielding materials and a methodology for designing effective shielding for X- and γ-rays ranging in energy to 100 MeV in both diagnostic and therapeutic radiation facilities. These reports were updated and superseded in the early 2000s.

Through this period, both ICRP and NCRP revised and updated their basic recommendations for radiation protection as more biological information and epidemiological analysis gave increased insight to radiation effects in humans.[85,86,128] These recommendations were always guided by the principles adopted by the two organizations:

- no practice shall be adopted unless its introduction produces a positive net benefit;
- all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account; and
- the dose equivalent to individuals shall not exceed the limits recommended for the appropriate circumstances.

NEW MILLENNIUM

Although vision impairing radiation-induced cataracts were well-documented by 1906, it was not until about 2009 that cataract induction as a result of low dose chronic exposure was documented in radiologic technologists and operators performing interventional fluoroscopy, especially as the complexity of interventional procedures increased.[131–133] This along with data from the atomic bomb survivors, Chernobyl liquidators and other groups, led the ICRP and NCRP to markedly reduce the recommended limit to the lens of the eye to a level consistent with whole body dose limits.[134,135]

During the period 2000–2010, medical imaging experienced almost a complete switch from film-based to digital receptors with the potential of reduced doses. There has not yet been a documented substantial reduction in operator doses in developed countries as a result of introduction of digital technologies however, there has likely been a large dose reduction to operators in developing countries many of whom were using fluoroscopy for almost all imaging to avoid the cost and shelf life issues of film.

A variety of current medical activities that involve radiation should still be considered as potentially delivering measureable external doses to staff, including: conventional or complex fluoroscopic examinations, fluoroscopic guidance for orthopedic and other surgical procedures; cardiac catheterization and other types of fluoroscopically guided interventional procedures; CT-guided interventional procedures; nuclear medicine examinations including those involving conventional radionuclides (*e.g.* ^{99m}Tc) and PET (*e.g.* ^{18}F, and novel PET agents); as well as therapeutic administrations of radioactive materials.[136–142]

Increasing use of radioactive materials in diagnostic imaging, especially PET, multimodality imaging (PET/CT, PET/MR), nuclear medicine imaging (*e.g.* stress tests, scans), and localization studies (*e.g.* sentinel node, radioactive seed localization), have increased the potential for staff exposures.[3] This is especially true for patient positioning, injection of dosage, and preparation of doses, both in nuclear medicine suites and outside traditional radiology departments. In addition, several institutions are building in-house cyclotron and radiopharmaceutical facilities and developing non-traditional PET isotopes such as ^{64}Cu, ^{68}Ga, ^{86}Y, ^{89}Zr, and ^{124}I that involve emissionof high-energy γ-rays, in addition to 0.511 MeV annihilation photons. These uses present challenges for occupational exposures with respect to shielding and radiation protection issues.[114,143]

The ICRP and NCRP continue to produce strategic and specific guidance and recommendations associated with both patient and worker protection under the principles of justification, optimization and the use of dose constraints, or numeric protection criteria (for planned occupational exposures). A majority of both ICRP and NCRP reports apply directly or at least are pertinent and relevant to the evolving medical practice.[144,145] Cardiologists and vascular surgeons are relatively new but rapidly expanding populations using interventional fluoroscopy and who benefit from expanded and detailed radiation protection education.[146,147]

Permissible occupational exposure levels have been significantly reduced[148] since the initial discovery of X-rays and radioactive material (Table 2). Lauriston S. Taylor[149] cautioned on how best to interpret such a trend (already evident as of 1957) in a 1957 lecture entitled "Radiation Exposure as a Reasonable Calculated Risk," "*…at none of these levels has there ever been developed any positive evidence of damage to the individual. In the main, these successive lowerings represent improved compromises between goal-zero, and capability. Again, capability has been made possible by technological advances.*"

CASTING A VISION: FUTURE OPPORTUNITIES AND CHALLENGES

The odyssey of radiation uses in medicine is a remarkable story that spans three centuries of innovations and applications. The early euphoria and unlimited enthusiasm of radiation as the cure for all maladies, however, was quelled when medical workers and practitioners developed serious medical conditions including sarcomas, cataracts, skin cancers, severe dermatitis and aplastic anemia. The international medical organizations responded, radiation protection committees were created, radiation protection guidance was recommended, and radiation exposure and dose quantities defined. Paralleling the seemingly unbounded increase in the medical benefits of accurate and improved diagnoses of disease coupled with the remarkable improvement in therapeutic modalities and patient survival, was a greater understanding of adverse health consequences occurring among medical radiation workers and patients. Radiation protection guidance evolved[88,89,146,147,150] and continues to do so today.[91,151]

Protection guidance tries to keep pace with the rapidly changing uses of medical radiation around the world. Constant vigilance is critical as are partnerships with and programs within medical radiological societies, government agencies and manufacturers. New health studies continue to emerge, including those of medical radiation workers.[119,152] New health benefits continue to emerge, both in diagnostic and therapeutic applications in radiology. The invisible rays are improving the health of the people, curing many maladies. Radiation protection committees are at the ready to assess new knowledge on potential health risks and provide guidance as needed to avoid adverse consequences without curtailing patient benefits.

As we look back to springboard toward the future, it seems fitting to conclude with a quote from the poet Edmond Spenser (The Faierie Queene) as did William Crookes in his initial descriptions of "radiant matter" in 1879 at Sheffield[8,153] :

> "Yet all these were, when no man did them know,
>
> Yet have from wisest ages hidden beene;
>
> And later times things more unknowne shall show.
>
> Why then should witless man so much misweene,
>
> That nothing is but that which hath seene?"

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