The Early Years of X-rays

Wilhelm Conrad Röntgen was a 50 year old professor at the University of Wurzburg in 1895. Expelled from school for refusing to name a fellow student who drew a caricature of a teacher, he had entered academic life by taking an entrance examination to the Zurich Polytechnic School. He became assistant to the Professor of Physics there, Augustus Kundt (best known for his resonant tube experiment from school physics), and went with Kundt to Wurzburg. Kundt tried to get Röntgen an academic post there but failed. Röntgen then took a series of posts at Strasbourg, Hohenheim, back to Strasbourg (now as Professor of Theoretical Physics), Giessen University and then, in 1888, back to Wurzburg.

He had worked on a variety of topics in physics: specific heat of gases, thermal conductivity of crystals, polarisation of light, electrical characteristics of quartz and compressibility of fluids. He was now Professor of Physics and Director of the Physical Institute at the University of Wurzburg [1] and took an interest in the developing field of cathode rays.

Röntgen liked to repeat the experiments of others when he entered a new field and he was operating a Lenard tube, a discharge tube with a thin aluminium window that allowed cathode rays to escape to the outside. He covered the tube with a black card – to shield its fluorescent glow – so he could check some of Lenard's work and noticed that a barium platino-cyanide screen[1] lying nearby became fluorescent. He soon realised that he was dealing not just with cathode rays but with a new phenomenon. This

1 Some versions have "crystals" rather than a screen as the fluorescent object

discovery was made on the evening of 8 November 1895 and he worked in secret for the next seven weeks investigating the properties of these new rays with a fluorescent screen and then photographic plates. He found that the rays originated from the fluorescing area of the tube (and later from an aluminium target if he introduced one) and that they travelled several metres through air.

But his most striking discovery was that these x-rays, as he called them, could pass through objects and affected photographic film. He made radiographs of a set of weights, a piece of metal and the bones of his wife's hand.

He handed his first paper to the president of the Physical Medical Society of Wurzburg on 28 December 1895 and it was immediately printed and distributed. Röntgen contacted colleagues around the world – Lord Kelvin and Sir Arthur Schuster in the UK – sending them, on 1 January, the paper and radiographs (no copies went to the USA). An English translation was made by Schuster's assistant, Arthur Stanton, and it appeared in *Nature* on 23 January 1896 with an accompanying letter by A A Campbell Swinton (the Scottish engineer later to promote a television system based on cathode rays) and the radiograph he had taken of a hand on 13 January. On the 18 January the *British Medical Journal* carried a paper by Schuster announcing the discovery [2].

Most people got to know by another route [1]. The Austrian paper *Neue Frei Presse* published an account on 5 January and this was picked up by the British *Daily Chronicle* which published a short article the following day (spelling Röntgen's name as "Routgen"). The *Manchester Guardian* printed a longer account on 7 January with the London *Evening Standard* publishing on 7 and 8 January. The *New York Times* reported "Professor Routgen's experiment" on 16 January. Röntgen gave a public lecture on 23 January in Wurzburg [1] and it started a kind of fever.

When asked by a magazine reporter what he thought when he observed the x-rays, Röntgen gave his celebrated answer: "I did not think; I investigated".

He obviously considered this an appropriate comment because he said it again to Sir James Mackenzie Davidson, who visited him soon after the discovery [3].

Others had, previously and unknowingly, generated x-rays. Lenard, in the investigations of cathode rays that led to his receiving the Nobel Prize in 1905, believed he had detected the waves (as he then thought) passing through his hand. This was probably an observation of x-rays and, when he became a leading Nazi, he claimed that he had discovered the rays before Röntgen [1]. Other experimenters had also produced the rays and even experienced some of their effects. For example, Arthur W Goodspeed of the University of Pennsylvania had been photographing sparks and discharges in 1890 and found strange images on the plates. These could later be attributed to the production of x-ray [4].

Since every laboratory of consequence already had the equipment necessary to study cathode rays they could produce x-rays and Röntgen's discovery was quickly confirmed. Campbell Swinton made the first radiograph in the UK on the evening of 7 January with an anode made from platinum sheet. It was poor and he made better ones the following day. The first in the USA was just days later. The first images of "clinical conditions" in the UK were made soon afterwards, probably by John Hall-Edwards in Birmingham [5] on 12 January when he stuck a needle in his associate Ratcliffe's hand and radiographed it. Schuster, in Manchester, radiographed a dancer's foot in February – she had a needle in it – and kept the image on his desk until his death [2].

The communication by Röntgen to Lord Kelvin in Glasgow found its way to John Macintyre, the physician recently appointed to the position of 'Medical Electrician" at Glasgow Royal Infirmary. He had worked with Kelvin, then in his 50th year in the chair of natural philosophy, and the amateur scientist and patron Lord Blythswood, to build the hospital's Electrical Room to administer the then-popular techniques of electrotherapy. He soon reproduced Röntgen's results and before the end of January was giving a demonstration to colleagues.

In 1896 alone some 50 books and pamphlets and nearly 1000 papers were published on x-rays. The term "skiagraph" (shadow picture) was used for a while but "radiograph" was soon widely adopted. The *Archives of Clinical Skiagraphy* were started in May 1896 and its title became *Archives of the Rontgen Ray* in 1897.

The first US x-ray was taken by A E Wright of Yale on 27 January 1896 and Dr. Henry Louis Smith, a Professor of Physics at Davidson College in North Carolina, performed one of the first x-ray experiments in the United States: in February 1896 *The Charlotte Observer* published his x-ray photograph of a bullet in the hand of a cadaver. The excitement provoked by x-rays is illustrated by the actions of three Davidson College students, Osmond L Barringer, Eben Hardie, and E Pender Porter. On the night of January 12, 1896, the three students bribed a janitor to let them into the medical laboratory on campus. After three hours of experimenting, they produced an x-ray photograph of two rifle cartridges, two rings and a pin inside a pillbox. They also radiographed a human finger they had sliced from a cadaver with a pocket-knife.

"We kept our picture and escapade a secret and it was not until later that we realized we were making history for the college instead of just breaking the rules", Barringer wrote some years later.

The extraordinary popular impact of the discovery has been well documented. The fascination with seeing into a living body was to some extent balanced by a concern for a loss of privacy. The latter was perhaps summed up in *Photography* soon after the discovery:

Thro' cloak and gown – and even stays
Those naughty, naughty Roentgen rays

We were, after all, still in the reign of Queen Victoria [6].

Röntgen published two more papers on x-rays. The first in March 1896 showed that x-rays could make air conduct electricity (although he could not explain this) and reported that x-rays could be produced by anodes of all the substances he tried but that platinum, inclined at 45 degrees, gave the most penetrating rays. In the second, published in 1897, he showed that any material exposed to x-rays would itself emit x-rays and studied the output of the rays from various tubes. He never gave another talk on x-rays and abandoned them in 1900 to return to his work on crystals when he moved to the University of Munich in 1900. He retired in 1920 but continued to work at the University until his death on 10 February 1923. He was awarded the first ever Nobel Prize for Physics in 1901 for his discovery and investigation of x-rays.

In England medical opinion on the potential value of x-rays, sceptical at first, was swayed by lectures, notably one by Silvanus Thompson at the Medical Society of London on 31 March. In February the *British Medical Journal* commissioned Sydney Rowland to investigate and he then produced 13 influential weekly reports between February and June [2].

Röntgen, in his first paper, speculated that because these new rays shared some characteristics of light (they formed shadows, caused fluorescence and affected photographic plates) they might be related. He suggested that they might be longitudinal (rather than transverse) waves in the ether [7]. The serious possibility that x-rays were electromagnetic was considered early on and Lodge in July 1896 [8] was able to draw on theoretical reasons to suggest that they were transverse waves of extremely short wavelength far beyond the ultra-violet. He also thought that "the Becquerel rays", which had subsequently been found, were " a less extreme extension in the same direction" - so he was not right about everything.

The conclusive demonstration that x-rays were electromagnetic waves was not made until 1913. Diffraction gratings were well-known for optical wavelengths. These were composed of very fine opaque lines drawn very close to one another in a regular way. If the repeat of the lines is close to the wavelength of light then light passing through it will show a diffraction pattern. Von Laue suggested, in 1913, that the regular atomic structure of crystals might make a sufficiently fine diffraction grating for x-rays. Friederich, Knipping and Laue placed crystals of various materials in a fine beam of x-rays falling on a photographic plate. They found that, as well as the spot caused by the main beam, there was a pattern of spots from the diffracted radiation that showed conclusively that they were dealing with a wave. The theory and practice of x-ray diffraction from crystals was rapidly developed by the Braggs and this led to a powerful tool for chemists and biochemists for the rest of the century.

By the end of 1896 x-ray tubes had been improved vastly. The 'Focus' tube was developed by Herbert Jackson, from earlier work by Crookes. Its concave cathode directed the cathode rays into a small spot on an target anode set at 45 degrees, giving much sharper pictures. It was established that the best target materials were those of high atomic weight and that platinum was the best practical material (tungsten and uranium were better experimentally but were more difficult to work with). It was generally used in a thin layer on nickel because of cost. Initially those experimenting with x-rays had to construct their own equipment from scratch but the interest was so great that, within just a year of the discovery, the American General Electric company had produced a catalogue of x-ray equipment. Although it was still necessary to assemble the parts yourself.

Both induction coils and Wimshurst machines (or similar electrostatic generators) were used to provide the high voltage for the tubes. The induction coils were better once reliability problems associated with the interrupter were solved. The power supply was generally an integral part of the package because of the unavailability or unreliability of mains power supplies and it was, anyway, two decades before good insulated cables became available [9]. As improved generators appeared, targets of osmium and tantalum were used, and this, with better arrangements for heat dissipation, allowed currents to rise ten fold to 50 mA [2].

The early x-ray tubes depended on the presence of some residual gas (they became called "gas tubes") for the electric discharge to take place: it was the positive ions colliding with the cathode that produced most of the electrons. In operation some of the gas became adsorbed onto the inside of the tube increasing the vacuum. This led to the tube becoming "harder": a higher voltage was required and the x-rays became more penetrating while their intensity decreased. A number of systems for keeping the pressure in the tubes nearly constant were devised. Some involved heating palladium membranes and allowing hydrogen to permeate into x-ray tubes; others used heat to release absorbed gases from mica and charcoal. By 1900 automatic regulation was possible using an auxiliary spark to heat mica and release absorbed gases. However, the popular description of a gas tube as "a glass bulb surrounded by profanity" [9] was appropriate for a while yet. But the industry grew quickly and when the British Röntgen Society held a competition for x-ray tubes in 1901 twenty-eight tubes were submitted; the winner came from Germany.

Improvements in resolution of radiographs came when it was realised that the scattered and secondary x-rays generated in the tissue of the body were a major cause of blurring. In Switzerland, Otto Pasche devised a system to address this as early as 1903 [10] but the first practical system was that of the German Gustav Bucky (later after emigration to the USA to become Albert Einstein's doctor and be present at his death) in 1913. Bucky arranged two grids - one between tube and patient and the other between patient and photographic plate – in such a way that only un-scattered rays could reach the plate. Much better resolution resulted but the image was overlaid with an image of the grids. The system was later improved by the American Hollis E Potter who used a single slatted grid that moved around during the exposure, so it left no clear image. The Potter-Bucky diaphragm is still used. A side effect of the system was the possibility of getting larger images. Since large photographic plates were difficult to handle, this encouraged the search for a film-based system [10].

Early radiographs were made onto glass photographic plates coated with emulsion on one side. The emulsion had a habit of slipping off during developing and it was often the job of a junior to wax the edges of the plates to help to keep the emulsion in place . It was quickly established that a thicker emulsion was better than a thinner one and before the end of 1896 double-sided plates were being produced, although they were too expensive for general use. John Carbutt in the USA developed an improved emulsion in 1896 reducing the exposure required. Paper was tried instead of plates in 1897 but it found only limited use because of inferior image quality.

Eastman Kodak also improved emulsions and produced special x-ray film in 1913. This became commercially available in 1918 although it was not widely used, because the images were not of the high-quality produced on plates, until 1923. The film was coated with emulsion on both sides ("Dupli-Tized") and this improved its sensitivity. However, the film base was celluloid nitrate and highly inflammable: when the x-ray film store at Cleveland Clinic caught fire, 129 people died. In 1924 Eastman introduced the cellulose acetate base as safety film.

The intensifying screen was suggested by Campbell Swinton in January

1896 and in April he found that, with a photographic plate in contact with a fluorescent screen, it was possible to get an image of a hand in a few seconds rather than 1 to 2 minutes. The image quality was not very good and he discovered that a finely-powdered screen material gave good resolution but poor response; increasing the powder grain size improved the response but the resolution deteriorated [11]. However, priority should perhaps go to Michael Pupin in Chicago. He was trying to x-ray the hand of a wealthy New Yorker in February 1896. The man had been hit in the hand with shotgun pellets and could not bear to unclench it for long enough to get a good look with a fluorescent screen. Pupin put the screen on a photographic plate and obtained an acceptable image in just a few seconds. However, it was to be a long time before the intensifying screen was developed and used routinely.

Röntgen's original discovery led directly to the fluoroscope. In this simple device a fluorescent screen covered the end of a light tight box and it could be observed through an eyepiece. This meant that the shadow pictures could be observed in daylight. It was one of the most used devices in the early days of x-rays with the advantage of simplicity and the immediacy of real-time observation. It was developed as the hand-held Cryptoscope by Professor Enrico Salvioni of Perugia using barium platino-cyanide for the screen, and by February 1896 several UK investigators had built copies [2]. It was improved by Edison, who selected calcium tungstate as the best screen material, and coined the name Fluoroscope. He later characteristically claimed the invention. It was common practice for a radiologist to check a set-up by putting his own hand between the x-ray tube and the screen and checking the image, a practice that was to be the cause of much pain and suffering later on.

There were some remarkable technical achievements early on. For example, Macintyre from Glasgow produced the first x-ray movie - a frog's leg in motion – and showed it to a meeting of the Royal Society in June 1897 [2].

The first major advance in x-ray tube design was the invention of the modern high-vacuum thermionic tube by William David Coolidge in 1913. Coolidge had found a way of making the metal tungsten suitable for use as a filament in electric light bulbs while working for General Electric in the USA. It was used by GE and they produced their first tungsten light bulb in 1910. Coolidge then turned his attention to x-ray tubes and introduced a tungsten filament as the cathode. This, when heated by passing an electric current through it, gave off a controllable supply of electrons. When the vacuum was improved (no ionisation of gas was necessary to create the electrons at the cathode) Coolidge had a reliable tube that allowed the voltage and current to be controlled independently. Radiologists could then accurately control the hardness of the x-rays produced (it depended on the voltage across the tube) and the intensity of the beam (it depended on the current heating the filament).

The Coolidge tube was so effective that the inventor's hair fell out after he tested it (he later used a severed human leg for experiments and lived to be 102). It was quickly taken up in the USA but its adoption in Europe was held up by the First World War so for a decade or more the gas tubes continued to be used.

X-rays were a novelty: the Kaiser had his arm x-rayed, the British Prime Minister Lord Salisbury and his wife had their hands done in 1896 and the Portuguese queen, Emilia, required her ladies in waiting to have their chests radiographed to show the damage caused by tight corsets [9]. However, there were many serious uses in a remarkably short time as two examples from the USA show.

The first US medical radiograph was on 3 February 1896 by Edwin Frost an astronomer at Dartmouth College, New Hampshire. A boy who had injured his wrist was seen by Dr. Gilman Duboi Frost, Edwin's brother. Edwin was asked to make the radiograph and produced the first image of a Colles fracture. A photograph exists of the moment of exposure.

Over the Christmas period of 1895, Tolman Cummings was shot in the leg in a Montreal bar by one George Hodder. The local hospital was unable to find the bullet but an x-ray taken at McGill University (later Rutherford's home for a while) in early February 1896 clearly showed it and was used by surgeons to get it out. The bullet and x-ray were produced in court and Hodder was convicted and sentenced to 14 years. This was thus probably the first time x-rays were used as evidence in a court case anywhere. The first dental x-rays were taken in Germany in January 1896 – needing a 25 minute exposure. C Edmund Kells took the first in the USA in New Orleans in April [9].

As 1896 progressed there were almost endless radiographs of bone fractures and of needles and bullets embedded in bodies with increasing clinical value. But there were also important, more experimental developments. Radiographs were obtained of tumours and, even in 1896, radio-opaque substances were being used to visualise organs. Within a very short time Cannon in the USA was using pearl buttons and bismuth mixed with food to show the gastro-intestinal tract and the Austrian Hashek had injected a metal-salt solution into an amputated hand and arm and produced the first angiogram. Soon a liquid contrast medium was introduced into the stomach as the bismuth meal (later the less toxic barium sulphate was used). The opaque meal to diagnose ulcers and cancers of the stomach and duodenum was developed in Vienna in 1904 by Reider and popularised in the UK by workers such as A E Barclay and Sebastian Gilbert Scott

Traumatic injuries of war were quick to receive the benefits of diagnostic x-rays. The first use of x-rays for examining military casualties was by the Italians in their Abyssinian War of 1896 [2]. The British Army's first radiographs were made at the now-derelict Royal Victoria Hospital at Netley near Southampton in November 1896 and by mid-1898 sets were installed at Aldershot, Woolwich, Dublin and Gibraltar and portable sets had been ordered for field use.

The first British involvement in combat use was during the Graeco-Turkish war of 1897 when the British Red Cross, financially supported by an appeal by the *Daily Chronicle*, sent two hospital units to help the Greeks. They were accompanied by an "absolutely complete" x-ray outfit. The team was led by F C Abbott, a surgeon from St Thomas's Hospital in London and the man in charge of radiography was Robert Fox Symons (later Sir Robert). Over a period of six weeks, they treated 114 war casualties and took some 50 or 60 radiographs. It was a clear success in showing that good radiographs could be taken in forward hospitals. A number of problems were experienced in transporting the equipment safely but the major difficulty was in obtaining power; they depended on the warship *HMS Rodney* to recharge their accumulators [2]. A rival German Red Cross Society team took an x-ray set to support the Turks and this was similarly a success (except for problems with accumulators).

The first use with British troops on the battlefield was probably in 1897 when an "apparatus" was sent to the North West Frontier, then the border between India and Afghanistan and now part of Pakistan. An army of 100,000 was in the field to put down a rebellion of the local tribesmen and about 40,000 of these were in the Tirah Expeditionary force on the Tirah plateau. Here there were 23 field hospitals and, because of the appalling problems of transporting wounded, they were undertaking a great deal of surgery. Several hundred x-rays were taken by the regimental surgeon of the Coldstream Guards, W C Beevor using a prototype apparatus developed by A E Dean of Hatton Garden, London. This, with its three Cossor x-ray tubes, came in a collection of wooden cases carried, suspended on poles, over the rough terrain by Indian bearers. His problems were associated with batteries and the tendency for the emulsion of his Eastman x-ray papers to melt. A memorable image came from his work: that of the bullet fragment lodged in the leg of General Wodehouse. The general's wound had been probed under intense fire from the tribesmen and his stoicism had been praised in the British newspaper. When the wound had failed to heal after several weeks, one of Beevor's x-rays showed part of a bullet had been left in his calf muscles. On his return Beevor's report played a part in promoting x-rays as an important tool in military surgery [2].

The expedition of General (later Lord) Kitchener was sent to repossess the Sudan and avenge the death in 1885 of Gordon in Khartoum. The expedition was eventually supplied with x-ray equipment but only after cross words had been exchanged in the House of Commons [2]. After this, x-rays were firmly established as a part of military medicine.

The effects of radiation on the skin - hair loss and burns -suggested that it might have some value in treating skin conditions and other ones which were resistant to then-current treatments [12]. After all, ultra-violet radiation was already in use for some of these. So, there were some early rather crude attempts to use the new x-rays as therapeutic tools. At the end of January 1896 , Grubbé tried to treat an advanced breast cancer and lupus vulgaris, Voigt in Hamburg treated cancer of the nasopharynx in February and Despeignes tackled cancer of the stomach in July [4]. In December 1896 Leopold Freund made the first considered use of x-rays as a therapeutic tool when he irradiated a large hairy birthmark (hirsuites) covering the entire back of a 4 year-old girl. The treatments were spread over more than 10 irradiations each lasting 2 hours and the growth was removed but the patient suffered episodes of serious ulceration over many years. However, she was examined in 1956 (she walked in off the street) and found to be well but with some damage to the lower back and again 15 years later when she was 75.

In 1896 the physicist Michael Pupin in Chicago made what seems to have been first therapeutic application of x-rays in the USA for cancer in treating a woman with breast cancer [13]. Pupin had no medical background and is perhaps now best known for his work on long-distance telephony. By the early 1900s radiotherapy was being used quite extensively and successfully (and perhaps often unwisely) for non-malignant skin conditions conditions such as tinea capitis, acne vulgaris, eczema, lupus, skin tuberculosis [14] as well as for skin, breast and other cancers. Many who did used the technique saw it as a form of cauterisation rather than anything more sophisticated but during the 1910s it became rather clearer that it was indeed skin conditions that might benefit most with the equipment and techniques then available.

Within six months of Röntgen's announcement several of the leading hospitals in London had set up permanent x-ray units. Some were based on existing electrotherapy departments.

Possibly the first in Britain was set up by the surgeon Thomas Moore at the Miller Hospital in Greenwich after he made early (March 1896) radiographs with the scientist William Webster. Moore was Treasurer of the Röntgen Society and one of the first editors of *Archives of the Roentgen Ray* and when he died in 1900 his radiography was taken up by John Jewell Vezey, amateur scientist and another Röntgen Society man, who worked unpaid until he died at work in 1906. The apparatus installed in Vezey's time was based on a 12 inch coil with mercury interrupter and could be used on the wards with accumulators. Webster, a founder member of the Röntgen Society, had the first reported incidence in the UK of radiation "sunburn" on his right hand [2] .

The London Hospital extended its Electrotherapeutic Department to include an x-ray service. The Department head, W S Hedley, took on Ernest Harnack as an assistant and they built up the x-ray service, constructing some of the equipment themselves. Their work covered a wide range of conditions but they were probably most useful, in the early years, with their radiographs of fractures and of needles stuck in hands – an occupational hazard in the tailoring industry centred around the hospital.

The Department grew over the next few years and in 1903 it split into two. One part was concerned with the treatment of skin lesions by electrical treatment and x-rays, with x-rays being used for rodent ulcers and ringworm. The other part dealt with the diagnosis and treatment of other conditions using x-rays. This second department was headed by E Reginald Morton, an electrotherapeutist who focussed on x-ray therapeutics as a natural extension of his electrical work. A further reorganisation in 1909 led to the appointment of S G Scott as the Department head and he became the hospital's first full-time radiologist with a primary interest in diagnosis [2].

In 1905 an article in *Archives of the Röntgen Ray* described two treatment rooms: one for skin tumours and diseases and one for other tumours. Some protection measures were in place: the x-ray tubes were enclosed in lead glass to protect the operator and the doses to the patient were measured by time and by pastille methods. Patients were protected from soft x-rays by lint soaked in calcium tungstate and then dried [15]. However, ringworm, a condition prevalent at the time and resistant to other treatment, was treated by irradiation of the scalp in a set of three barber chairs located side by side. Within 20-30 years many of the patients has developed radiation-induced rodent ulcers of the scalp. The method continued to be used until 1960 [15].

The other major London hospitals developed along similar lines. Barts extended its Electrical Department to include x-ray diagnosis and skin condition treatment in 1896 and dealt with over 200 patients in its first year (rising to over 1000 in its sixth).

St Thomas's had the distinction of being the location of the first radiograph taken in a London hospital at a demonstration on 13 February 1896. The equipment was improved (a Jackson focus tube was quickly introduced giving much shorter exposure times) and used operationally from then on with a Department being set up in October 1896. In 1897 over 400 patients were examined. By 1914 St Thomas's was the leading hospital in radiology in the UK.

Guy's Hospital was slightly later. The first x-rays were attempted in April 1897 but it was probably a year or two before the x-ray service became a permanent feature with the appointment of two radiographers in 1899. By 1904 there was a clear division between electrical treatment and x-rays.

The explosion of interest in the rays meant that exploitation far outstripped understanding and when potential hazards were seen they were widely ignored. So, the absence of shielding around the early x-ray tubes resulted in considerable injury to the operators and the problem was compounded by the common practice of operators looking at their own hand with a fluorescent screen to test the apparatus.

Early warnings of the potential hazards came within a few weeks of Röntgen's discovery. In the UK, L R L Bowen, in a talk to the London Camera Club on 12 March 1896 – reported in the *Lancet* –warned that x-rays might produce effects like sunburn. In April L G Stevens reported in the *British Medical Journal* that people exposed to x-rays suffered sunburn and dermatitis. Warnings also came from the USA: in March Thomas Edison reported sore eyes after extended exposure [16] and William J Morton saw burns [14]. Dermatitis and hair loss were reported by J Daniel of Vanderbilt University after he taken a one hour exposure of a man's skull.

An example from America illustrates some of the cavalier attitudes to x-rays. In the summer of 1896 Herbert Hawks was demonstrating x-rays in Bloomingdale Brothers' Store in New York. Hawks, an assistant to Dr. Pupin at Columbia University, experienced radiation burns and received an unusual diagnosis.

> Mr. Hawks, during the afternoon and evening of each day for four days, was working around his apparatus for from 2-3 hours at a time. At the end of the four days, he was compelled to cease active work, owing to the physical effects of the x-rays upon his body. The first thing Mr. Hawks noticed was a drying of the skin, to which he paid no attention, but after a while it became so painful it was necessary to stop all operations. The hands began to swell and assumed the appearance of a very deep sunburn. At the end of

> two weeks the skin all came off the hands. The knuckles were especially affected, they being the sorest part of the hand. Among other effects were the following: the growth of the fingernails was stopped and the hair on the skin that was exposed to the rays all dropped out, especially on the face and sides of the head. The chest was also burned through the clothing, the burn resembling sunburn. Mr. Hawks' disabilities were such that he was compelled to suspend work for two weeks. He consulted physicians, who treated the case as one of parboiling. [2]

The response to the revelations of these effects was varied, indeed Hawks thought his experience was probably largely due to electrical effects [17]. Others suggested that such effects came from the electric sparks in the high-voltage generator, from ultra-violet(uv) radiation, from chemicals used in developing plates, from ozone generation in the skin and from faulty technique [18]. The lingering doubt that radiation was the cause of injuries should have been eliminated when, in November, the American physicist Elihu Thomson purposely exposed the little finger of his left hand for half an hour close to an x-ray tube. Over a period of a week or two the finger became swollen, sensitive and painful. He was convinced that the effects were caused by the "chemical activity" of the rays and issued a caution. (One of his recommendations was "Do not expose more than one finger") [18].

Thomson's report prompted a number of others to publish their experiences of x-ray burns and the eminent UK physician, Sir Joseph Lister said in his presidential address to the British Association for the Advancement of Science in September 1896:

> It is found that if the skin is long exposed to their action it becomes very much irritated, affected with a sort of aggravated sunburn. This suggests the idea that a transmission of the rays through the human body may be not altogether a matter of indifference to internal organs… [18].

However, in January 1897 John Hall-Edwards, the man who probably made the first clinical x-ray in the UK and had exposed himself for hours each day for a year, could write:

> We have heard so much about the effect of the x-rays upon the skin; this I think must be due to some idiosyncrasy of the operators, for although I have myself been experimenting daily for

> the last eleven months I have failed to notice anything of the kind. [19]

Hall-Edwards had a long interest in photography and microphotography and was already an Honorary Fellow of the Royal Photographic Society before working with x-rays. By 1899 his opinions on x-rays were changing:

> Continued and protracted exposure to the rays at varying distances from the tubes has an effect upon the hands which although unpleasant is not dangerous. It interferes with the growth and nutrition of the nails. The skin round the roots of these become red, irritable and cracked, and the nails themselves thin and brittle. Most constant workers suffer in this way.[19]

By 1902 he was developing painful sores and warts and a photograph of "chronic dermatitis" printed in the *Archives of the Röntgen Ray* (of which he became editor in 1903) was probably of his own hands. At the annual meeting of the British Medical Association, held in Oxford in 1904, Hall-Edwards described his condition and this was subsequently published in the *British Medical Journal*. In this illustrated article about his own conditions he strongly urged young workers to take every possible precaution before it became too late [19]. The pain was "as if bones were being gnawed away by rats" [50]. By 1906 his left arm was useless and carried in a sling. In 1908, when cancerous growths were found, his left arm was amputated just below the elbow and the fingers of his right hand were removed. He advised caution [19] and went on to become a Birmingham City Councillor before dying in 1926.

Other cases developed. For example, at the pioneering London Hospital, Harnack had three assistants, Reginald Blackall, Ernest Wilson and Harold Suggars. By 1903 they all had radiation injuries. Wilson took a series of photographs of his hands showing progressive bony damage leading to malignancy and died in 1911. Harnack ultimately had both hands amputated. Suggars and Blackall worked for longer and helped to establish the College of Radiographers [2].

In the USA the cases of Clarence Dally and Mihran Kassabian received wide publicity and had great impact. Dally had joined Edison after he left the US Navy where he had been a Chief Gunner's Mate ("a little fellow, but a specimen of perfect manhood" according to his surgeon). He worked with Edison from 1896 and was responsible for testing tubes and assisting Edison with his x-ray development. For the tube testing he often placed his hand between the fluoroscope and the tube. His hair soon began to fall out, his face wrinkled and his hands developed dermatitis. The skin condition worsened over several years, leading to failure of the blood vessels in his left arm, and a cancerous condition developed. By 1901 it was necessary to amputate his left arm and in 1903 fingers were removed from his right hand. The right arm was later amputated and Edison supported him until Dally's death in October 1904 [20]. The experience caused Edison to give up work on radiation. He abandoned work on a fluorescent lamp based on radioactive material and said: "I could make the lamp all right, but when I did so I found that it would kill everybody who would use it continuously" [20].

Mihran Kassabian, through his work as a photographer and his interest in electrotherapy became the "skiagrapher" and instructor in electrotherapeutics at the Medico-Chirurgical College and Hospital in Philadelphia. By combining his work as a skiagrapher with that of electrotherapist, he was able to confer the status of a clinical department on

Figure1: Kassabian's laboratory

radiology. Over a two-year period he examined more than 3000 patients and exposed more than 800 radiographs and became director of the Roentgen Ray Laboratory at the Philadelphia Hospital in 1903.

He developed x-ray "burns" by April 1900 and, by 1908, he had a malignancy on his left hand. Kassabian described the progress of the illness

Figure 2: Kassabian's hands

(and the amputations he underwent) at professional meetings and in his 1907 textbook *Roentgen Rays and Electrotherapeutics.*

He died in 1910 of radiation-induced cancer. His exposure of the risks of x-rays was another important factor in making workers take protection more seriously

These were just two of the many x-ray workers who suffered delayed but appalling injuries from x-rays. In 1936 a memorial was erected in Hamburg to the early pioneers of x-rays who suffered radiation injury or lost their lives due to their work.. Of the original 169 names from 15 nations, 14 are from Britain. The British names are Reginald Blackall, Barry Blacken, John Hall-Edwards, Cecil Lyster, Stanley Melville, Hugh Walsham, John Chisholm Williams and Ernest Wilson, William Ironside Bruce, William Hope Fowler, J W L Spence, Dawson Turner, James Riddell and G A Pirie. The last six were Scottish.

The citation reads:

> They were heroic pioneers for a safe and successful application of x-rays to medicine. The fame of their deeds is immortal.

The British Institute of Radiology compiled documents to support the inclusion of thirty-four additional British doctors and nurses. Most of these died of the complications of skin cancer, a few from aplastic anaemia or leukaemia [19].

Marie Curie died of a "pernicious aplastic anaemia" on 4 July 1934 and it was immediately, and for a long time, assumed that this was a result of exposure to radium. However, when her ashes were reburied, with those of her husband, in the Pantheon in Paris in 1995, the measurement made by French radiation protection experts showed that the levels of radiation associated with them were quite low. It therefore seems possible that the cause of her death was exposure to x-rays during the First World War [14,21].

For several years after Röntgen's discovery injuries were usually seen as temporary and superficial but, by about 1905 most workers were taking some precautions [2]. With the increasingly powerful x-ray set-ups available, it became even more important.

Since the common practice of checking a set-up by placing the hand in front of the fluorescent screen was probably the single biggest cause of injury, the invention of the Chiroscope in 1903 must have made some difference. This was a skeleton hand with simulated flesh mounted behind a fluorescent screen. The Osteoscope was a similar device using a complete forearm [22].

The human arm, Chiroscope and Osteoscope were possibly adequate ways of checking apparatus for diagnostic use but there was obviously a need for a more quantitative measurement of tube output. One of the earliest methods for measuring this was based on the the comparison between the brightness of a fluorescent screen produced by x-rays and that of some standard source. Basing his system on a method where the standard source was an acetylene lamp, Guilleminot, in 1907, used as the standard a fluorescent screen irradiated with a radium source of known strength [4]. His unit was the "M". Butcher, in 1908, used a similar method and expressed his results in "radion" or "radio-lux" units in analogy with visible sources.

While the primitive methods of the arm and Chiroscope might have been adequate for diagnostic applications, a quantitative method was also needed for controlling the dose received by patients in therapy – where an over-exposure could have very serious consequences.

The dose delivered in therapy was measured by several means but pastilles that changed colour and film strips that blackened were developed from about 1902. The pastilles were calibrated against a standard epilation dose. One, the pastille of Sabouraud and Noiré using a barium platinocyanide compound, was available in booklets. It simply changed colour (or rather tint) at the epilation dose and this was called the B or pastille dose. Lower doses could be measured by placing the pastille closer to the tube than the organ being irradiated and applying the inverse-square law. Another system, prepared by Holzknecht in 1902 (and based on a "secret" recipe involving potassium chloride and sodium sulphate), allowed easy comparison between the pastille tint and a graduated standard and was based on the H unit chosen so that the epilation dose was 5H. The original calibrations were made with unfiltered radiation but adjustments for epilation doses were not too large with filtered radiation [23]. The pastilles survived as measurement systems for a long time; the Sabouraud and Noiré pastille devised in 1904 was still in use in the 1930's [23].

Strips of film were also used as the dose meter. Kienböck in 1905 used strips of silver bromide paper, later known as Kienböck strips, which were placed on the patient's skin during irradiation. After development in a standard way they were compared with a greyness scale in an instrument called a quantimeter [22] calibrated in x units, where 10x corresponded to the epilation dose. The strips had the disadvantage of requiring processing but they did provide a permanent record of exposure.

Ionisation as a measure of radiation was considered early on and both gold-leaf electroscopes and ionisation chambers were suggested as measurement devices. In fact, Paul Villard, the discoverer of gamma-rays, suggested a unit based on the charge liberated by radiation as early as 1908. However, the technology that allowed routine, reliable measurements of ionisation was not to become available for some years and most practitioners came to rely on a system like the pastilles. This led to a wide range of dose units and little scope for intercomparison. Mould has listed more than 50 units that were suggested or used up to 1937 [22].

Measuring the penetration of the x-rays was important to diagnosis and therapy. Initially, using the Fluoroscope, the classification of radiation hardness was based directly on tissue and bone penetration but penetrameters soon became available. The earliest was actually made by Röntgen in 1897 but credit is generally given to Benoist in 1902 who used the same principle for his radiochromometer. This was a standard thin silver disc surrounded by aluminium foils of increasing thickness. It was placed behind a fluorescent screen and the brightness behind the silver disc was compared with that behind the aluminium foils. When the two brightnesses were the same, the thickness of that aluminium foil gave a measure of the penetrating power. Other instruments based on the same idea were developed elsewhere [22].

Shielding of the tube was unusual before about 1908 but some practitioners were careful throughout. Francis H Williams of Boston can be seen with a protective box around the tube in a 1902 photograph [22] and he remarked later that he thought penetrating rays like x-rays must have "some effect upon the system" and took precautions accordingly. Williams's early caution came from his brother-in-law and collaborator, the remarkable William Rollins.

Rollins, a Boston dentist, stood for what we would now call a precautionary approach to x-ray safety. One of his experiments, reported in February 1901, resolved the debate addressed by Elihu Thomson's exposure of his fingertip. Instead of sacrificing a body part, Rollins put a guinea pig in a Faraday chamber – a set of electrically-earthed boxes that excluded any electric fields – and exposed it to an x-ray source outside the box. The exposure lasted two hours per day and, after 11 days, the guinea pig died. A second died, after similar treatment, after 8 days.

It led Rollins to propose three precautions:

- physicians should wear glasses that keep out x-rays when using fluoroscopes
- x-ray tubes should be kept in shielded boxes with a small window to give a cone of radiation no larger than needed
- patients should be shielded except where necessary for examination or treatment.

Just two weeks later he reported another disturbing result. This time he placed a pregnant guinea pig in the chamber and irradiated it: the foetus it was carrying died. It was not unusual for physicians to examine pregnant women with x-rays to check the size of their pelvis and the condition of the foetus and Rollins cautioned against this. It should have been clear that these effects were a result of x-ray exposure and not some obscure electrical effect but not everyone was convinced and it was suggested that the guinea pigs had either suffocated or developed some infection. Rollins had in fact disposed of these objections by having retained a set of control animals, who showed no ill effects. One of Rollins's more alarming observations was – or rather should have been – that the guinea pigs that died showed no radiation burns – possibly because the softer x-rays were filtered out by the surrounding boxes. It was an early indication that there were hidden effects, much more serious than transient skin burns or cosmetic changes [17].

Rollins did not simply exhort radiologists to take more care but devised a number of practical ways for them to protect themselves and their patients. The enclosure of the x-ray tube already mentioned was improved in two ways over the next year or two. He invented a shutter that could be opened remotely and an adjustable rectangular collimator that could be used to achieve the smallest usable area of illumination of the patient. He suggested improvements to intensifying screens and tried to discourage the practice of "warming up" the tube while the patient was exposed to the beam. He also, probably, proposed the first numerical protection standard when he suggested that the test for adequate shielding of a tube should be to place a photographic plate on the outside. If the plate was not fogged after a 7 minute exposure, then the protection was sufficient [17].

Rollins was a man ahead of his time. His impact was limited in the USA because the growing x-ray community was not disposed to accept that the astonishing new rays might have a serious downside that might limit their spread. He results and proposals may, anyway, not have been widely known outside the Boston area[2] and they certainly did not cross the Atlantic.

Protective wear, as an alternative or supplement to shielding, appeared as early as 1898 when Price in the USA proposed the use of lead-rubber gloves. By 1905 the Crusader-like Friedlander full protective suit (with apron, gloves, hoods and spectacles) was on the market in the USA for $30 [9]. Other similar suits were available. Gloves and aprons became routine in Britain in about 1905 [2]. In 1908 Hall-Edwards published a list of 10 rules including: shielding of the tube with just a small aperture opposite the patient, shielding of the operator by a moveable panel, keeping your distance from the tube and using an opaque apron and lead glass spectacles when viewing a fluorescent screen. He emphasized that the effect of x-ray exposure was cumulative [2].

Even at the London Hospital, where the radiography team had already suffered the effects of radiation, protective measures were slow arriving. However, by 1908, the practice of checking with the hand had been stopped, tubes were enclosed in lead-lined boxes and, in 1909, shielded cubicles were installed for therapy.

The skin was clearly the organ most damaged by x-rays and some practitioners made use of the filter devised by George E Pfahler in 1905 [24] to protect themselves and patients. This simple disc of leather removed the less penetrating rays that damaged the skin but allowed the more penetrating ones, that produced the radiograph, through. This was not all good news: some therapeutic irradiations had been limited by skin reactions and when these were reduced much higher doses could be delivered to deeper tissues [14].

So, by perhaps 1910, the dangers of acute and disastrous tissue damage were widely recognised and there were some straightforward protection measures being adopted. The means of measuring larger doses were available and were used for control of patient exposures. Together these things could, if sensibly applied, reduce and perhaps eliminate the dreadful acute effects – and within a few years professional bodies would step in with recommendations on protection to do just this. However, many of the early workers were to die because of their injuries and even more were to suffer and die from unsuspected long-term effects that were a long way from being

2 his principal work “Notes on the X-Light” was privately published in Boston in 1904

understood.