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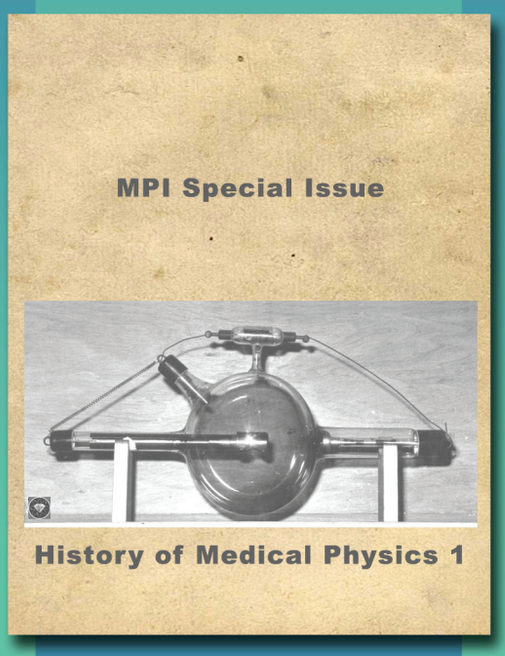

The Journal of the International Organization for Medical Physics

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MEDICAL PHYSICS INTERNATIONAL

THE JOURNAL OF

THE INTERNATIONAL ORGANIZATION FOR MEDICAL PHYSICS

MEDICAL PHYSICS INTERNATIONAL

The Journal of the International Organization for Medical Physics

Aims and Coverage:
Medical Physics International (MPI) is the official IOMP journal. The journal provides a new platform for medical physicists to share their experience, ideas and new information generated from their work of scientific, educational and professional nature. The e- journal is available free of charge to IOMP members.

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EDITORIAL

The profession of Medical Physics along with the associated technology and medical procedures have benefited from extensive innovations and developments for now more than a century. Knowledge of these developments and applications provides a foundation for the continuing contributions of physics and engineering to advances in medicine and healthcare along with an appreciation of our medical physics history and heritage.

The goal of the IOMP History of Medical Physics Project is to document this significant era of achievements and provide insight into the motivations and developments that have established Medical Physics as a major science in the field of medicine and global healthcare.

This first Special Issue of the IOMP Journal Medical Physics International (MPI) begins the series of publications linked with that project, announced last year at MPI, 2017, No1, p. 68-69 (April 2017).

Over the past year the project was announced at various professional events – the AAPM Annual Conference in Denver, the IPEM Annual Conference in London (Esher); the Asia-Oceania Congress of Medical Physics in Jaipur; the IOMP RCB - Regional Coordination Board (including the Presidents of all professional Federations), etc. With the assistance of the RCB Questionnaires were sent to all IOMP Member Societies, almost all of which are now completed. This included an invitation for various organizations and individuals to consider developing materials for the project.

The plan is for the project to be published in 12 volumes. In this Special Issue, prepared for publication during 2017-2018, there are three chapters from two of the volumes. The chapters are about the History of X-ray Tubes development, the History of Film-Screen Receptors development and the History of e-Learning development.

These were prepared to be used as Guides for the development of future chapters in this large project. Using the experience from another large project (e-Encyclopaedia of Medical Physics), we are aware that such Guides are setting important trails in the parallel work of various specialists from many countries.

It is obvious that the History is not a static publication and in future will be further upgraded with materials about new developments, projects and applications. We believe that the History of Medical Physics project will form a sound record of the developments of our profession. It is planned that the initial development of the project will take several years and it will be regularly upgraded in the future.

We welcome the contribution of colleagues from all societies in the various volumes of the History. To facilitate the progress of the development of this large project we included a session “IOMP project History of Medical Physics” during the World Congress in Prague (Monday, 4th June, 8-9 am).

We look forward to your further contributions to the Project

MPI Co-Editors: Perry Sprawls and Slavik Tabakov

IOMP PROJECT HISTORY OF MEDICAL PHYSICS

(SELECTED CHAPTERS)

X-RAY TUBES DEVELOPMENT - IOMP HISTORY OF MEDICAL PHYSICS

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Content

Studying the history of medical X-rays and the evolution of the technology of its sources has been sparking fascination and heuristic insight over more than a century, see e.g.[1–10]. Today vacuum electronic X-ray tubes remain the dominant and affordable sources of medical diagnostic X-rays, see [9] and [11], despite of their deficiencies, see [12]. This article will illustrate the various branches of the development of the technology, and briefly mention a few of those scientists, craftsmen, business leaders, and artisans, who have driven this field of innovation.Although many other

physical processes are employed to generate X-rays for special applications, it is expected, that bremsstrahlung (stopping radiation) from X-ray tubes will remain the dominant agent in medical X-ray diagnostics for the decades to come, see [11].

After initial remarks on the way X-rays entered the clinical routine, this paper, a part of the IOMP Project "History of Medical Physics", willdiscuss in depth the paths taken for improvement of medical X-ray tubes for radiography, angiography, dental and mammography application.

1. Enabling technologies and physics in the 19th century

Ongoing technical evolution culminated in Conrad Wilhelm Röntgen's discovery of X-rays, what happened at dawn of Friday, November 8th, 1895 in the Physical Institute of the University of Würzburg, Germany, see **Figure 1**. **Figure 2** shows the greenish glowing glass wall of a Crooke's tube, similar to the one which Röntgen used. The greenish color signals generation of X-rays by the electrons impact on the glass target. Their interaction with the atomic nuclei is essential to generate the highly energetic X-ray photons which are capable of penetrating at least portions of a human body, see e.g. [9], [13,14]. The required ingredients for this X-ray generation are free electrons, an accelerating electric field and a suitable target material.

Figure 1 Replica of C.W. Röntgen's first experimental equipment in his laboratory in Würzburg, Germany. It shows an actively pumped simple Crookes tube and a "large" Rühmkorff inductor. Röntgen discovered X-rays at dawn of Friday November 8th, 1895. (Photo taken at the German Röntgen Museum, Remscheid-Lennep, Germany.)

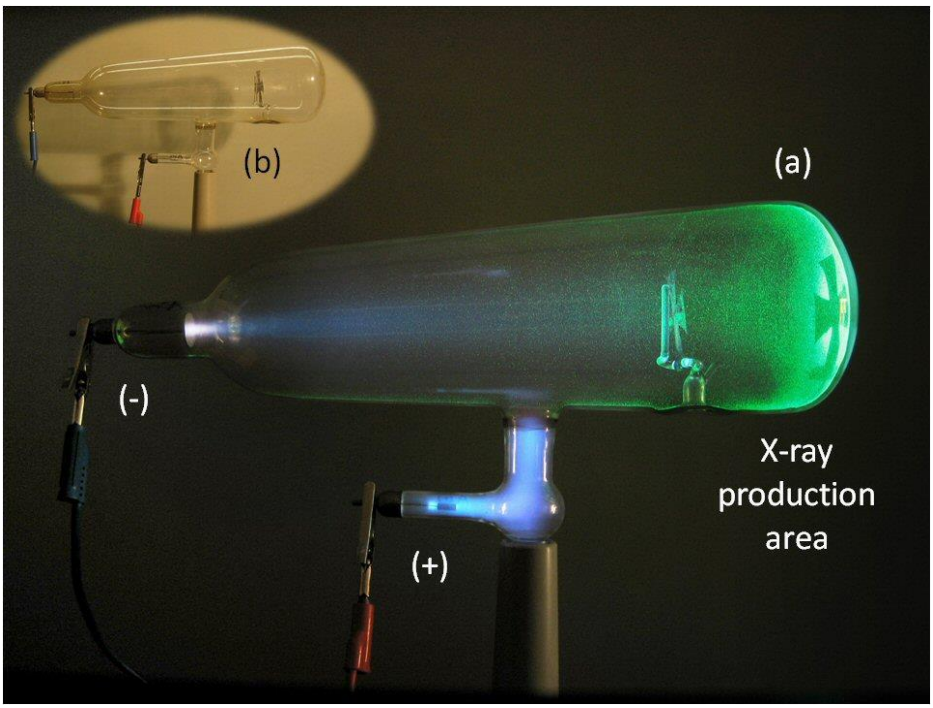

Figure 2 Crookes tube with shadow cross in use. X-rays emerge upon impact of electrons (cathode rays) on the glass wall at the right. Sub-picture: the uncharged tube. (Credit: D-Kuru, https://commons.wikimedia.org/w/index.php?curid=3068002, accessed Aug. 10th, 2017.)

Ancient Egyptians had already dealt with high voltage associated with the electric eel, as early as 2750 B.C. By 1644, Evangelista Torricelli evacuated glass tubes with falling mercury. In 1657, O. von Guericke attempted to separate large evacuated "Magdeburger" half spheres with horses, and failed. In 1705 F. Hauksbee, the elder, discovered sparks of light through partly evacuated vessels. W. Morgan may well have generated X-rays in 1785 during experiments on insulation by vacuum. Since the mid of the nineteenth century, voltages of tens of kilovolts at powers of tens of Watts have become available. J. Plücker generated free electrons in partial vacuum ("cathode rays") from 1858. Later J. W. Hittorf extended these experiments from 1869. Sir William Crookes deflected electrons magnetically. P. Lenard sent them through thin sheets of metal into free air.

1. Röntgen's discovery

Röntgenrepeated Lenard's experiments on cathode rays using a partly evacuated Crookes glass tube, a Hittorf tube or a Lenard tube, charged by a "large" Rühmkorff inductor, see [15]. He noticed a peculiar yellowish-green glow of a remote scintillator screen, see [13,14,16]. Without knowing, already five years before Röntgen's discoveryA. W. Goodspeed and his assistant W. N. Jennings had exposed photo plates to X-rays in Philadelphia, USA[17]. But, then, the team failed to have a final clue on the cause of the "destruction" of the plates. Also about five years beforeRöntgen's discovery I. Puluj from University of Strasbourg observed effects of X-rays and published a paper "Luminous Electrical Matter and the Fourth State of Matter", but he did not recognized the received rays as the X-rays. Röntgen, instead, identified the source of the miraculous agent. He experimented with different kinds of tubes, varied electrical and geometrical parameters, vacuum conditions, objects downstream of the obvious origin of X-rays, detection technology and identified key characteristics of the newly discovered radiation in a period of weeks. Although he speculated and, in

part, misinterpreted, Röntgen laid the firm ground for early diagnostic and therapeutic application of X-rays. Many of the effects, which he saw for the first time under controlled conditions, are still being employed. For instance, he shifted the origin of the X-rays by magnetic deflection of cathode rays, and, thus invented the magnetic focal spot deflection, which serves to this date to improve image quality in computed tomography (CT).Röntgen's discovery, and its application in medicine, triggered the establishment of the Nobel Awards, the first one being present to him in 1901.

2. Early clinical use and industrialization from 1896

Within the first year from the discovery, more than one thousand articles on X-rays were published worldwide. On January 12th, 1896 the first X-ray picture on the American continent was produced intentionally at the Davidson College, North Carolina, see [18]. On February 3rd, 1896 a diagnostic X-ray of the broken wrist was taken at Dartmouth College, Hannover, NH, USA. Yale University in New Haven, Connecticut, USA.

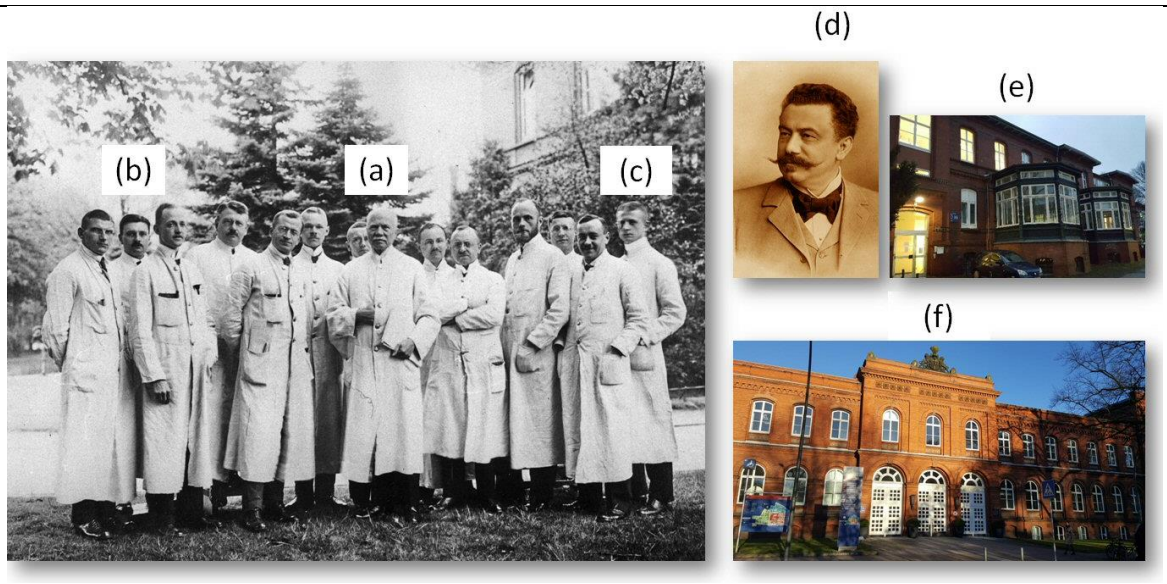

Figure 3 On March 20th, 1896, Hermann Kümmell (a), head of the surgical department and his team of the New General Hospital in Hamburg, Germany, initiated the first installation of an X-ray system worldwide - in a clinical setting in the preparation room of the new operation theater. Hermann Gocht(b), assistant of Kümmell and his friend and colleague Gustav Opitz (c) bought the first tubes from the glass blower C.H.F. Müller (d) in downtown Hamburg, and installed the system. (e) Actual pictures of the former operation house and (f) entrance of the hospital, now University Medical Center Eppendorf, UKE. (Photo (a) picture archive of Medizinhistorisches Museum Hamburg, Germany, UKE.)

Upon the initiative of the head of one of the surgical departments, Prof. Dr. Hermann Kümmell, the first sustained installation of X-ray equipment globally (in a public clinic) was put in operation on March 20th, 1896 in the "New General Hospital" in Hamburg, Germany. This institution still exists as the University Medical Center Hamburg Eppendorf (UKE, see [3],[16], [19], [20] and **Figure 3**). Kümmell had sent his assistants H. Gocht and G. Opitz to downtown Hamburg, who met with the glass blower C.H.F. Müller, whose company was later acquired by Philips, The Netherlands. Gocht, Optiz and Müller enthusiastically experimented with the new radiation and its sources and installed the first clinical equipment in a preparation room of the new operation theatre [1]. In those days, key users had to have a

[1]Translation from [20], page 779. Herman Gocht, recalling in 1914 the events which happened eighteen years before: *Meanwhile, March 20th, 1896, had arrived; on this day the first X-ray apparatus was put into service in the surgical department of Kümmell at the*

wide set of competences. They mastered medical physics, vacuum physics, high voltage electronics, and radiology. Later Gocht became a leading radiologist. Unfortunately, all three and many of their co-workers and staff died later from radiation-induced illness.

Work in physics laboratories went on as well. Less than a week after the first clinical installation in Hamburg, Siemens and Halske, Germany, filed the first X-ray tube patent, DE91028 on March 26th, 1896, see [8].**Figure 4**shows a sophisticated ion tube from C.H.F. Müller with automated gas "regulation" to reduce the energy of the emitted X-ray photons. The discharge process started at lower high voltage when the gas pressure was elevated. Many other companies also began producing X-ray tubes, see e.g. [21].

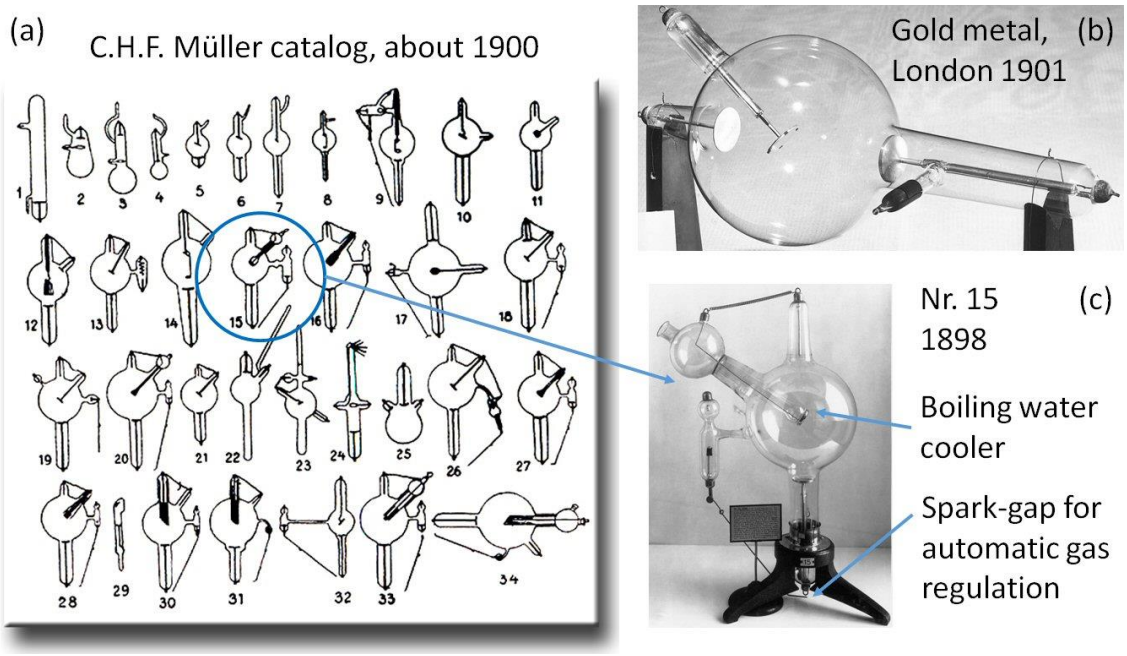

Figure 4 Ion tubesproduced bythe C.H.F. Müller AG, Hamburg, Germany (later Philips), about 1900. (a) Catalog from about 1900. (b) Müller ion tube, which won the gold medal for the best tube out of 28 in the London Roentgen Society competition 1901. The tube is on exhibit in the Science Museum, London, UK. (c) First water cooled tube after Prof Dr. B. Walter (physicist, Hamburg Germany). The automatic gas regulator is activated with an adjustable spark gap when the tube voltage rises due to falling gas pressure inside the glass envelope.

Figure 5illustrates how the high electron current density in an ion tube nearly destroyed the anode by surface melting. The C.F.H. Müller tube shown in **Figure 5** (a), serial number 82456, was produced in Hamburg, Germany, around the year 1910, and had indeed been in use. During the phase of negative charging of the cathode by the inductor, residual gas was ionized. Every ion impacting on the cathode cup at the right in **Figure 5** (d) released up to a dozen of initially slow electrons. The electrostatic field formed by the concave cathode cup accelerated the electrons between cathode and anode at the left in **Figure 5** (d), and focused them into the focal spot on the copper target (b). A melting pattern of the overheated focal spot is clearly visible. As copper evaporated and chemically reacted with residual gas,

Eppendorf Hospital. Kümmell had acquired the Rhümkorff apparatus (inductor) from the company Keiser and Schmidt in Berlin (Germany). It generated 25 cm long sparks (remark: this corresponds to a peak tube voltage of 80 kVp) *with the help of a Deprez platinum circuit breaker. We used two existing accumulator batteries from Reiniger, Gebbert and Schall, Erlangen, (Germany), which were otherwise used for light and cauterization in surgical manipulations. Florence Müller delivered the tubes to us.*
1.

and as ions were implanted in the cathode, the gas pressure inside the sealed vessel dropped over time. Manufacturers devised sophisticated countermeasures to overcome this problem. Gas releasing material in a remote appendix (c) was heated to re-fill the mobile tube such that the tube was “softened” again, i.e., it was then able to spark discharges at reduced high voltage and deliver photons with lower energy for better contrast of soft tissue.

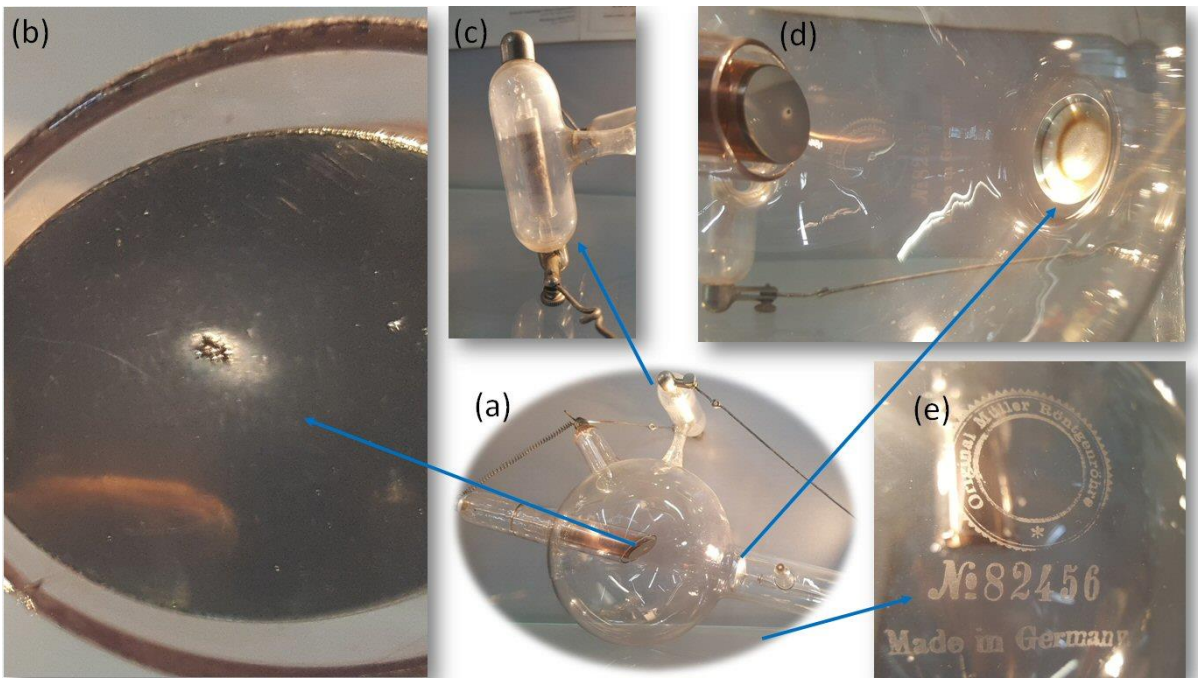

Figure 5(a) Ion tube similar to the one depicted in Figure 3. (b) Close-up view of the copper target. Repeated heavy electron impact overloaded the ellipsoidal focal spot. Melting and re-solidification led to cracking of the surface. (c) Regulator for gas production from heated potassium hydroxide, which engaged automatically when the discharge between anode and cathode ceased at insufficientgas pressure andthe inductor voltage exceeded a predefined level. (d) The concave cathode cup showssigns of oxidation and areas cleaned by ion impact. (e) Production label and serial number 82456 of the C.H.F. Müller AG, Hamburg, Germany (later Philips).

Reiniger, Gebbert and Schall AG, Erlangen, later Siemens, Munich, Germany, delivered tubes and scientific equipment to Prof. Röntgen as early as 1896. **Figure 6** demonstrates the ingenuity at the time, an ion tube for stereoscopic viewing.

Figure 6 Ion tube for stereoscopic imaging from 1912 after Dr. Fürstennau produced by the H. Bauer GmbH, Jena, Germany or Radiologie GmbH, Berlin, Germany. (Picture taken at the Siemens X-ray tube museum Rudolstadt, Germany.)

The company of E. Gundelach in Thuringia, Germany, another competitor, claimed to have produced 45,000 tubes by April 1905; C. H. F. Mueller, Hamburg, Germany - 50.000. Machlett New York, NY, established in 1897 (which became a division of Varian in 1989, now Varex, Salt Lake City, UT, USA) was probably the first producer in the United States, see [22]. Toshiba, Japan, began producing X-ray tubes in 1915, see **Figure 7**(this "Giba" tube was the predecessor of a large variety of products from the company).

Figure 7 Toshiba "Giba" x-ray tube, the first Japanese domestic x-ray tube, developed and commercialized in 1915by Toshiba Denki, later Toshiba Electron tubes & Device Co., Ltd (TETD, now Canon, Japan, group). Many types of x-ray tubes have been developed originating from this "Giba X-ray tube". (Courtesy of Toshiba Science Museum.)

3. Victims of X-rays and safety measures

The biological harm caused by high doses of the new radiation became obvious early on, see [18]. Many of the pioneering surgeons, scientists, and manufacturing staff, suffered severely. About 360 casualties have been reported at that time. Some radiographers sacrificed their own health when adjusting the equipment by imaging their hands before exposing patients. The exhibit of the cancerous hand of a radiographer can be seen at the German Röntgen Museum in Remscheid-Lennep, Germany. A number of people were also killed or injured by electrical shock. The increasing quest for reduction of the dose of ionizing radiation resulted in improvements of the X-ray beam quality by X-ray filters and radiation shields against primary radiation. X-ray sources were encapsulated and measures against scattered radiation taken. High voltage supply was shielded and improved safety standards were defined. Philips presented the "fully protected" Media™ and Rotalix™ tubes in the 1920s, see **Figures 12** to **14**. The Media™ tube allowed for changing the beam quality by an X-ray filter changer in a rotatable sleeve. Later, beam limiting devices (like the modern one depicted in **Figure 15)** were introduced, which allowed for adding selectable filters. Over the years, X-ray beams became harder and more monochromatic. Whereas, Röntgen first generated X-rays with a tube voltage of 80 kVp and a glass filter of a few millimeters thickness only, the minimal required equivalent filtration for typical radiographs grew to the current 2.5 mm aluminum equivalent. This helped reducing the skin dose of patients without jeopardizing the photon flux at the detector. Powerful angiography tubes, like the Philips MRC 200 0508 from 1990, shown in **Figure 36 (**with liquid bearing cooling and a large anode disk of 200 mm diameter) allowed for enhancing the thickness of the X-ray filter further to up to 0.9 mm copper. Still, no wait time for cooling was necessary. The workflow was even improved. The spectrum for this high-dose application became more and more monochromatic. For a comparison of spectra and intensities see [9], Figure 3.5.

4. High vacuum vs. semi-vacuum

In the era of ion tubes, discharge ionization of a well-adjusted amount of residual gas within a sealed glass envelope produced electrons at the cathode by ion impact. The discharge process dependedstrongly on the volatile gas pressure. Tube current and X-ray photon flux varied with the tube voltage in an unfavorable manner. They grew steeply with the high voltage applied. The X-ray intensity varied even more strongly. Instead, one wished to have the inverse correlation to optimally employ the thermal capacity of the focal spot area. Higher tube voltage, which causes a harder photon spectrum with better penetration of the object, would allow for lowering the current.

Already in the year 1882, E. Goldstein had successfully maintained gas discharges for the production of cathode rays (electron beams) at comparatively low gas pressure by heating the cathode, see [23]. But, given the required temperatures of much beyond 1000°C to provide for the full electron current, stable emitter material was missing. Instead, ions served to release the majority of electrons from the cathode to bear the main discharge. As many other scientists and engineers, J. E. Lilienfeld and W. D. Coolidge aimed at "softening" the X-ray tubes independent of the individual vacuum condition. This meant, enabling high tube current at low high voltage, in other words reducing the resistance of the tube. Lilienfeld attached an incandescent lamp to an ion X-ray tube.**Figure 8**depicts one of the many Lilienfeld tubes produced. A comparatively weak thermionic cathode, shown in **Figure 8 (b)**, comprised a heated filament and sent a small electron current through an auxiliary anode ring through a hollow cathode to pre-ionize the

residual gas in the tube. This starting process ignited and controlled the main gas discharge between cathode and anode inside the pink colored glass envelope shown at the bottom of **Figure 8 (a)**. The amplified electron impact from the main discharge on the tungsten inlay in copper eventually generated high X-ray flux. For the first time, Lilienfeld decoupled tube voltage (X-ray spectrum) and tube current (X-ray intensity) in abetter way than using the gas regulator.

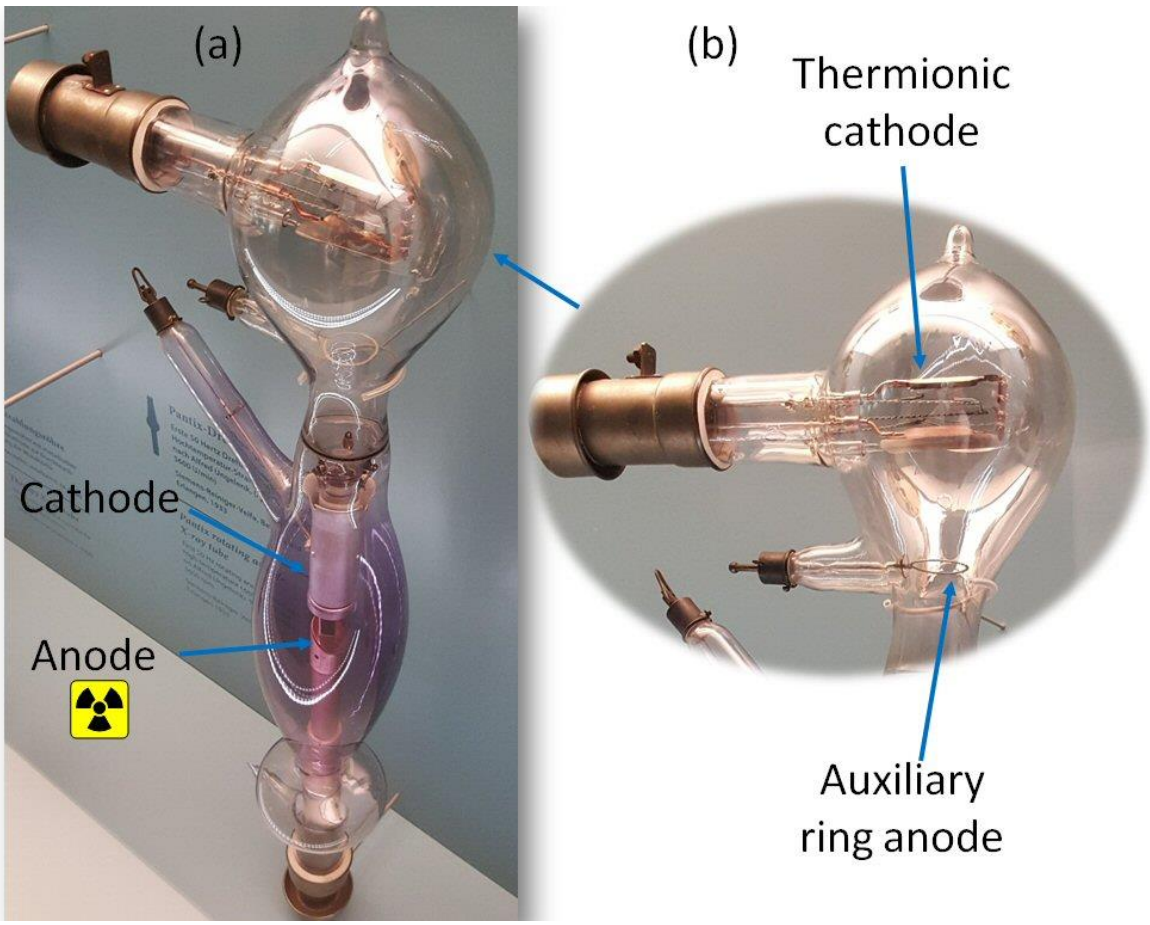

Figure 8 (a) Lilienfeld ion X-ray tube with thermionic electron production to pre-ionize residual gas. (b) Thermionic electron X-ray "softener", an electron source with auxiliary anode to pre-ionize the residual gas. This model marks the transition between ion tubes and high vacuum tubes. (Photo taken at the German Röntgen Museum, Remscheid-Lennep, Germany.)

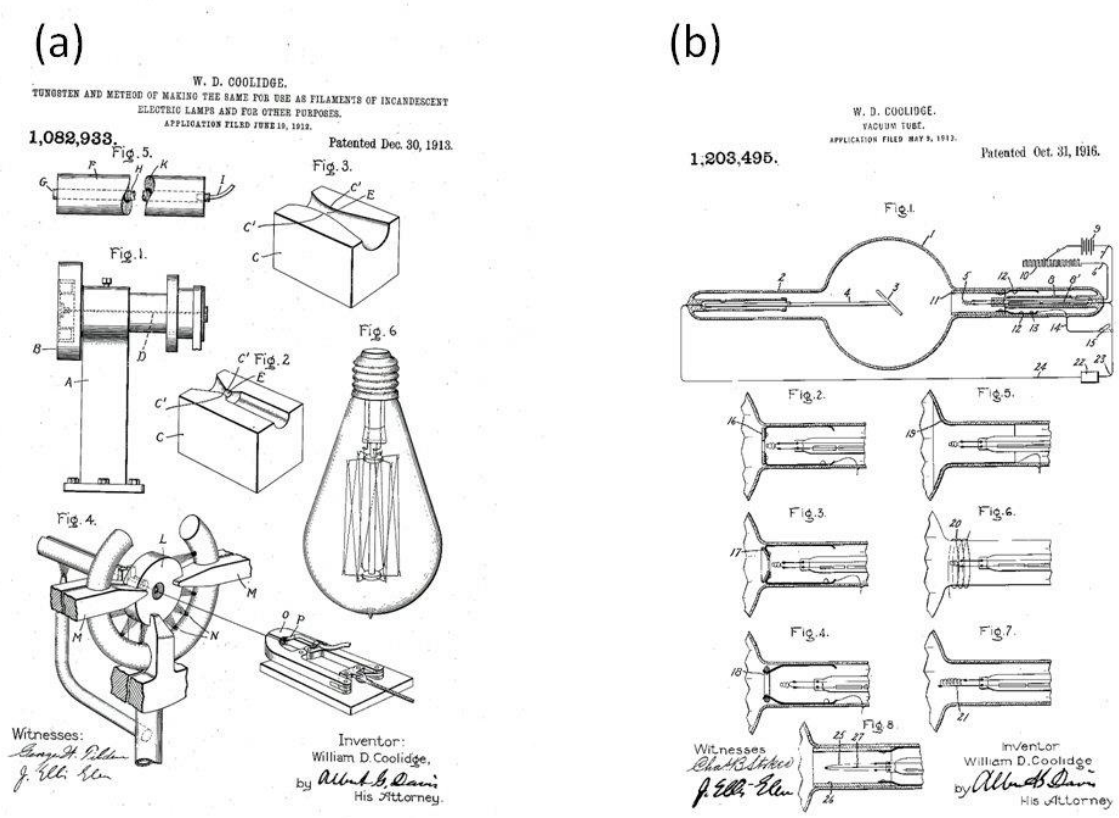

Figure 9 Photo of the illustration page of W.D. Coolidge's patent for the production of ductile tungsten, US1082933, filed in 1912. (Source: https://patentimages.storage.googleapis.com/pages/US1082933-0.png, accessed October 12th, 2017). (b) Photo of the 1913 patent of Coolidge for the hot cathode high vacuum x-ray tube.

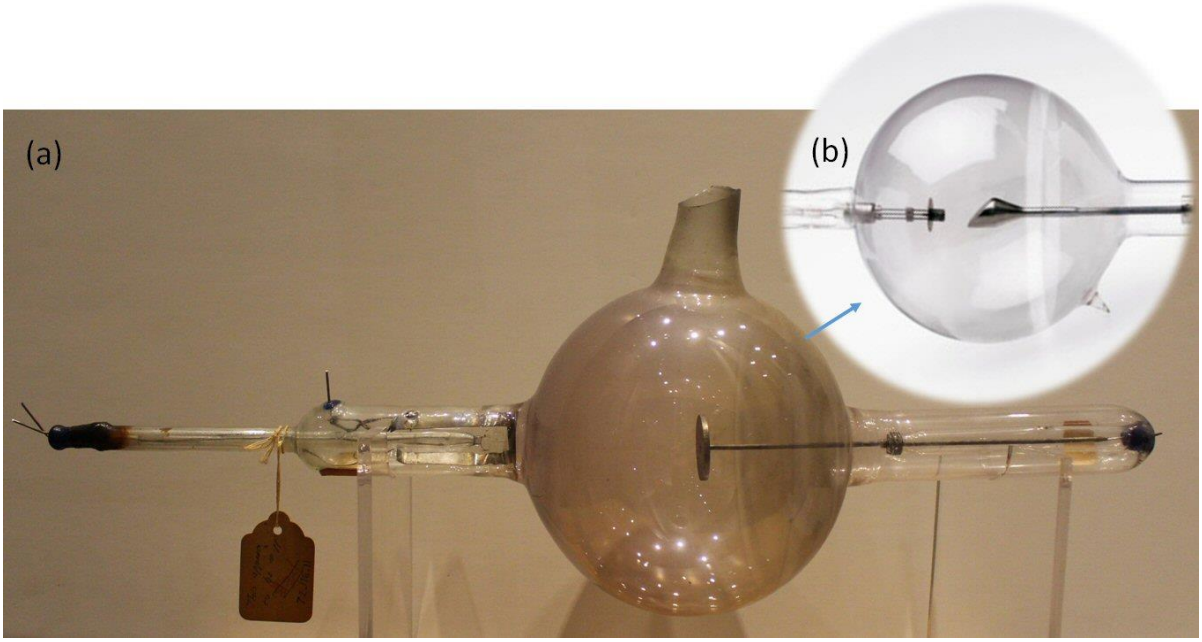

Figure 10 Photo, taken on April 30th, 1913, of one of the original experimental X-ray tubes used by W.D. Coolidge at the GE Research laboratory (Schenectady, NY, USA). It incorporated a tungsten thermionic emitter inside a highly evacuated sealed glass envelope. This concept allowed for very stable operation and repeatable results during imaging. For the first time, X-ray production was easily controllable by setting tube current independently from penetrating power and image contrast, which are a function ofthe tube voltage across the anode-cathode gap. Another "first" for this tube was the use of tungsten as a target material. (b) Close-up photoof a series production unit delivered from 1914. (Pictures courtesy of GE.)

Since 1905 W.D. Coolidge, who had before studied at the same institution as Lilienfeld (the University of Leipzig, Germany) was working at the GE Research Laboratory in Schenectady, NY, USA, primarily on incandescent lamps. Employing his invention of light emitting ductile tungsten wires, see **Figure 9**, he proposed a simplified X-ray tube. Coolidge demonstrated it publicly on December 27, 1913 for the first time in New York City at a dinner party given in his honor by Dr. Lewis Cole, who was the first physician to have his office equipped with the new tube. A ductile heated tungsten wire was capable of emitting the full tube currenteven at low tube voltage, without amplification by a gas discharge. Unlike the previous tubes, this one was highly evacuated. The tungsten wire withstood the high temperatures of about 2000°C, which were required according to Richardson's law of thermionic electron emission, see [9]. Coolidge cooperated with I. Langmuir (Nobel Prize for Chemistry 1932)at GE, who had graduated from the University of Göttingen, Germany in 1906. Coolidge was also able to reduce the distance between anode and cathode to avoid current limitation by electronic space charge, according to the Child-Langmuir law, see [9]. X-ray production became much better controllable, the tubes - more compact. **Figure 10**shows an ancient exhibit in the GE X-ray tube museum in Schenectady, NY, USA.**Figure 11** depicts Langmuirand Coolidge at GE Research in 1923, with the visiting J. J. Thomson.

Figure 11 I. Langmuir (left), W.D. Coolidge (right) from GE Research, Schenectady, NY, USA in 1923 with the visiting J.J. Thomson (middle), who discovered the electron, (Picture courtesy of GE.)

However Ion tubes were still improving.In 1916, the Victor X-ray Company of Chicago, IL (later to be acquired by General Electric, USA), produced ion tubes filled with hydrogen (to reduce the ion sputtering effect from electrodes) aiming to improve durability, to have better high voltage stability and to shrink the parallel spark gap. Reportedly there were instances of cold cathode tubes being employed as late as the 1960's. In the meantime, thermionic cathodes have taken over. Despite of many attempts to lower the emitter temperature by material with lower work function, notably barium and thorium, tungsten has remained the electron emitter material of choice in the chemically and physically harsh environment of an encapsulated X-ray tube. In the meantime, field emission cathodes captured some niche space in diagnostic X-ray tubes. Dedicated control grids in front of the emitters were needed for these field emitting devices to preserve the independency between tube voltage and tube current, the great former achievement of Lilienfeld and Coolidge.

The new technical simplification of the workflow altered the professional landscape. Before, the selection of the right ion tubes and adjustment of the technique factors required high technical skills. Radiographers had to be both physicians and physicists in medicine. The inventions of Lilienfeld and Coolidge marked the separation between radiologists, medical physicists and engineers.

5. Götze's line focus

Given a size of a typical imaging geometry of about a meter distance between X-ray source and detector, the X-ray fan beam is usually in the order of approximately 10° to. 20° wide in axial direction, perpendicular to the target. The surgeon O. Götze concluded from the nearly isotropic polar distribution of X-ray intensity from the anode and from the factthat we use only a small portion of the generated X-rays (max ca. 20° axial), that it would be beneficial to primarily use only a portion of X-rays, namely those which are emitted under a grazing angle. He proposed an axially elongated physical line focal spot, which maintains its (apparent) optical shortness when seen from the patient perspective (effective focal spot). A mapping of a rectangular Götze focus on the damaged target of a rotating anode tube is shown on **Figure 22**. The anode with blocked ("frozen") rotor was destroyed with two shots taken without rotation, which mapped the thermal focal spot by melting the tungsten top layer. Götze's patent from 1918 was first used by C.H.F Müller, later Philips, from 1922 onwards. Compared with a usual elliptical focal spot, the thermal capacity of the anode and the space charge limited electron current grew by nearly an order of magnitude. By May 1915, Elof Benson had filed the application for US patent 1174044, which may be interpreted as an early realization of a line focus. He proposed to direct cathode rays (the electron beam) onto a rectangular array of plane surfaceson the anode target, the cross section of which would resemble a saw-tooth pattern. However this structure was never commercialized.

This line focus concept has become standard. The anode angle is always minimized to maximize the power rating, adapted to the system geometry. Röntgen's first anode was an X-ray transparent sheet of glass with an "anode angle" of about 90°. He took off X-rays normal to the glass wall. As the available sources of X-rays became more powerful, the distance between tube and detector could be enlarged. As mentioned before, the characteristic angles of the X-ray fan beam shrunk to about 20° to 30° in each direction. The anode body produces a shadow in the image. The small fan angle allowed for limiting the fan of used X-ray photons to those, which are emitted very closely to the direction along the cone of the anode at a grazing angle of 10° to 15° of the center beam. It turned out beneficial with respect to image sharpness and power rating to use X-rays close to the shadow which the anode produces. Compared with Röntgen's glass anode, the physical focal spot size and its thermal capacity could be improved by nearly an order of magnitude. This attempt finds its limit in the socalled "heel effect". A few degrees close to the anode shadow,the X-ray intensity drops by intrinsic attenuation in the target. X-rays are generated several micrometers below the surface of the target and have to pass a few tens of micrometers of target material. This process also modifies the spectrum. Therefore, the anode angle has to match with the system geometry.

In 1923, Siemens patented a dual focal spot tube, which allowed optimizing the spatial resolution in the image. With this Biangulix™ tube, the company further introduced an anode target with two radially separated focal spot trackswith different anode angles in a rotating anode tube, see below, which allowed to fine-tune the trade-off between width of the X-ray fan beam, the desired spatial resolution and the power rating. Such a tube is depicted below in **Figure 18**. The image projection (and resolution) changes when a different focal spot is selected. Therefore, most of the modern tubes comprise superimposed focal spots with identical anode angle, typically between 9° and 15°. The small anode angle allows for a greater gain of X-ray flux than employing the relativistic forward enhancement of the X-ray production. Thus, shortly after Röntgen's discovery with a tube similar to the one shown in **Figure 2**, reflection targets have become

standard for diagnostic imaging. X-rays are produced at the same side of the anode where the electrons impinge, see e.g. **Figure 4**.

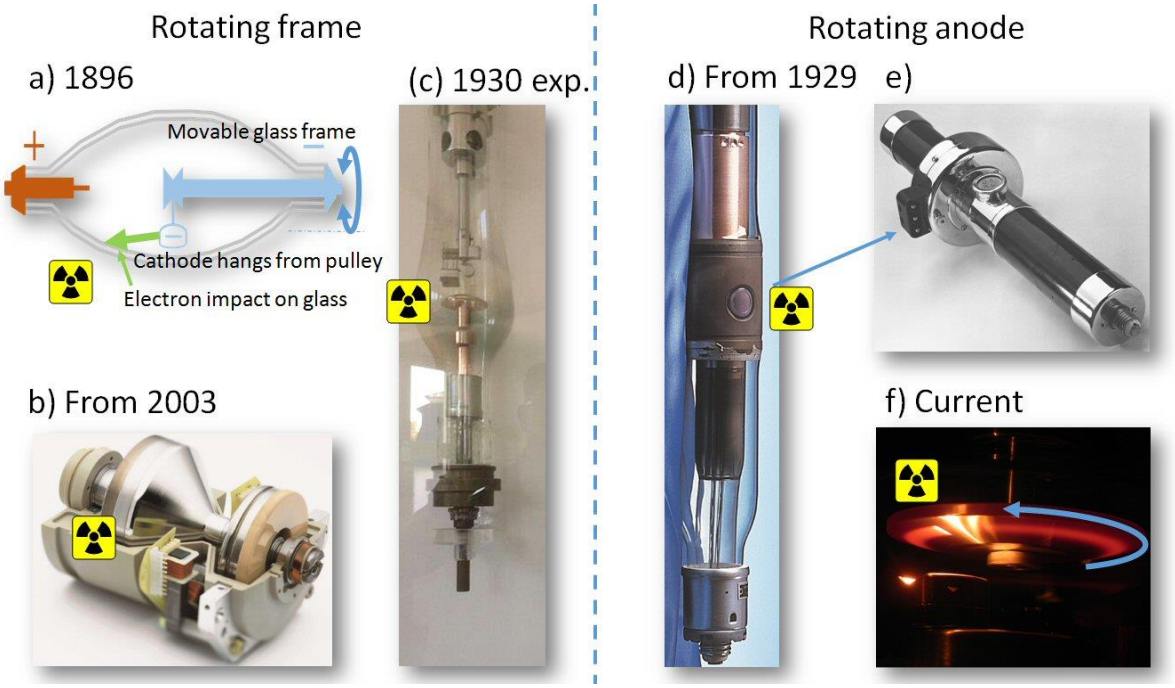

Figure 12 Competing concepts. Left: rotating frame, right rotating anode tubes:
(a) Firstidea of a movable target byR.W. Wood (before Nov. 1st, 1896): The cathode hangs from a pulley while the area of electron impact on the glass frame and may oscillate. (b) Siemens rotating frame tube of the Straton™series for CT with magnetic fixation of the electron beam. (c) Experimental rotating frame tube, with magnetic fixation of the cathode (1930), Phönix AG, Rudolstadt, Germany, and later Siemens. (d) 1st commercialized rotating target tube Rotalix™(1929) from Philips, (e) tube housing assembly for this tube. (f) Close-up view of a current rotating anode glass tube in operation.
(Figure (a) adapted from [22], Fig. 91), (b) courtesy of Siemens, (c) taken in the Siemens X-ray tube museum Rudolstadt, Germany, (d) and (e) courtesy of Philips.)

6. Rotating targets

The concept of the rotating target probably originated with R.W. Wood, see [24]. The point of electron impact determines the origin of X-rays in space. Moving the target with respect to the stationary electron beam, and introducing convection cooling in addition to heat conduction, leads to significant increase of electron beam intensity and reduction of exposure times of stationary anode tube by up to two orders of magnitude. A comparison can be found in [9]. Given the thinking in the year 1896, see **Figure 2**, Wood proposed a rotatable glass frame which acts as the anode, see **Figure 12 (a)**, while the cathode hangs from a pulley. Wood's concept is a precursor of the Siemens' Straton™ rotating frame tube for CT, see [25] and **Figure 12 (b)**. Notably, W. Coolidge from GE filed a patent application in 1915 for US patent 1,215,116, where he suggested rotating the tube frame, while keeping the focal spot stationary in space through deflection of the electron beam. Exactly this principle was realized 90 years later by Siemens for the Straton™, see also[9], paragraph 6.1.4. Siemens and Dunlee, Aurora, IL, USA (later Philips) experimented with other rotating frame tube concepts, using a magnetically fixed cathode. Such an experimental tube is shown in **Figure 12 (c).**

Another suggestion, rotating only the anode in the vacuum space inside the X-ray tube, came reportedly from E. Thompson at GE in 1896. But, it was not realized in practice until 1915 by W. Coolidge, who rotated the anode with a speed of 750 r.p.m. (12.5 Hz) and a focal track radius of 19 mm. The tube was not put on the market, however.

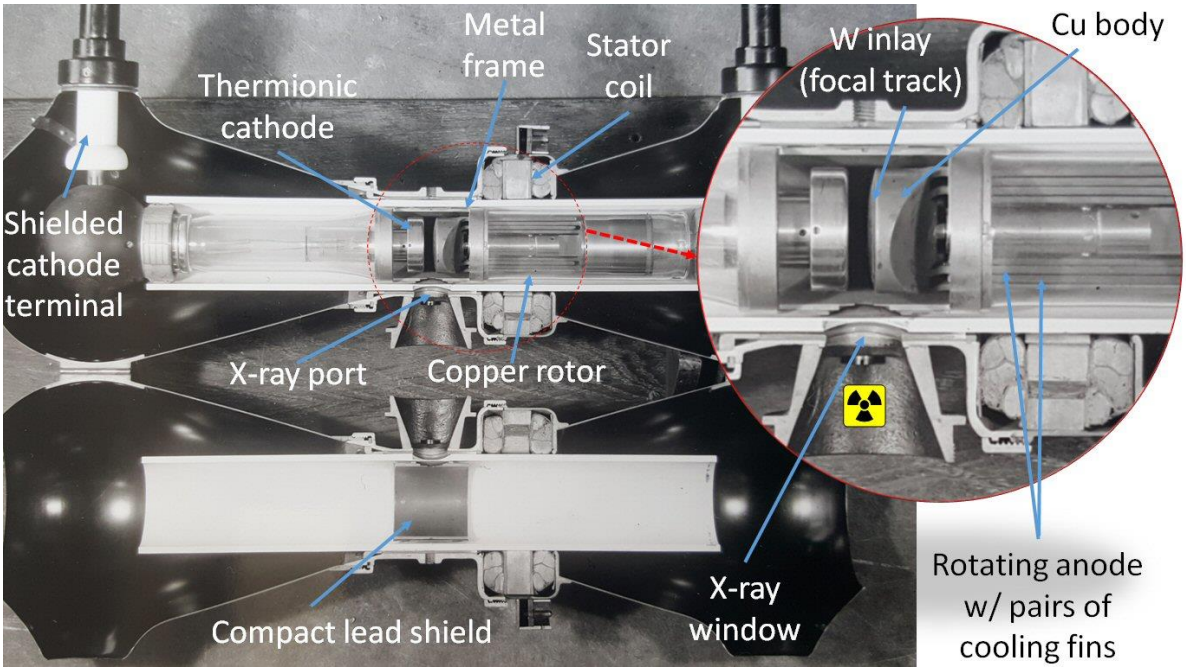

Figure 13 Cut out model of the first industrialized rotating anode tube in **Figure 12** (d). It allowed better heat dissipation at moderate temperatures, which otherwise the copper anode material restricted, A. Bouwers attached cylindrical cooling finsto the rotor, interleaved with stationary fins. Varian (now Varex), Salt Lake City, UT, USA, employed this concept again from the late 1990's for the MCS 7xxx CT tube series. Philips marketed the Rotalix™ tube as "fully" protected against leakage radiation and electrical shock. It was rated with peak power of up to 30 kW ina 2 mm wide focal spot (area 15 mm^2, focal track radius 2.5 cm,20 Hz rotor frequency). Compared with the stationary anode Metalix™(predecessor tube), the Rotalix™ tube featured a 9-fold improvement of the power rating, see also [9], figure 6.43.

Figure 14 "Fully protected" Philips Media™ tube from the 1920ies. A rotatable sleeve allowed for selecting the X-ray filter thickness. (Photo taken at the Medizinhistorisches Museum Hamburg, Germany, UKE.)

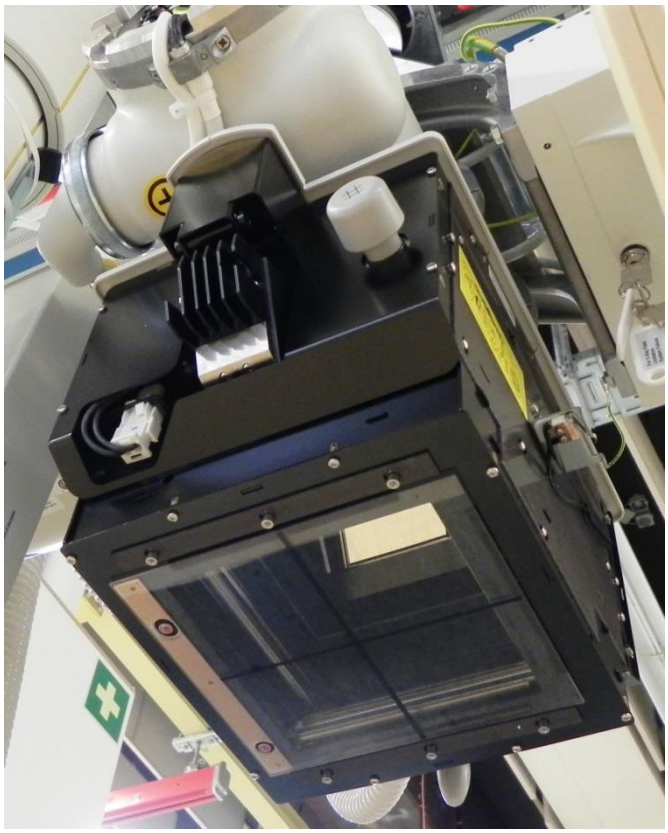

Figure 15 Current beam limiting device from Philips, with beam limiting apertures which allows adding of additional X-ray filtration. The cover was removed.

E. Pohl publicly demonstrated a rotating anode tube in Stockholm, Sweden in 1928. After this A. Bouwers of the newly established Philips National Laboratory in Eindhoven, The Netherlands, commercialized it with Philips under the commercial name Rotalix™ in 1929. This was the starting point of commercial availability of rotating targets. Bouwers introduced a rotating copper anode with tungsten inlay, see **Figure 12 (d)**, **(e)**, and **Figure 13**. However uncoated ball bearings in vacuum are subject of cold welding of steel with steel. After a few rotations, the rotors were blocked("frozen"). Bouwers solved this problem by using highly refined grease for lubrication. In these tunesa "squirrel-cage" motor transferred mechanical torque inside the vacuum, see [26]. As a downside of this concept, ball bearings practically interrupt the heat conduction from the anode to ambient. Moreover, the copper stem of the anode limited the allowable temperature to about 400°C. The low temperature hampered heat dissipation by thermal radiation. From a heuristic perspective, Bouwer's anode was a stationary anode on ball bearings. To improve this he introduced a finned anode structure, with interleaved stationary and rotating fins to maximize the heat radiating surface area. This idea was re-used in the 1980's by Varian (now Varex, Salt Lake City, UT, USA) for their high-end CT tubes with graphite-backed grooved anodes, see [9]. Four years after Philips , Siemens also launched rotating anodes by taking a slightly different pathsee [21]. Instead of a bulky large area radiator at moderate temperature, A. Ungelenk from Siemens in Rudolstadt, Germany, tried rotating high temperature tungsten disks to exploit the special characteristics of the Stephan-Boltzmann law, which states that the rate of heat dissipation is proportional to about $T_{anode}^4 - T_{ambient}^4$, T_{anode}

being the anode surface temperature and $T_{ambient}$the temperature of the environment. The first attempt with a rotating tungsten foil failed, see **Figure 16**. Instead, from 1933 on, the Siemens Pantix™ tube shown in **Figure 17**was delivered with a thicker and more stable all-tungsten anode. GE introduced a similar tube RT 1-2 in 1936, when Coolidge served as the director of the Research Laboratory.

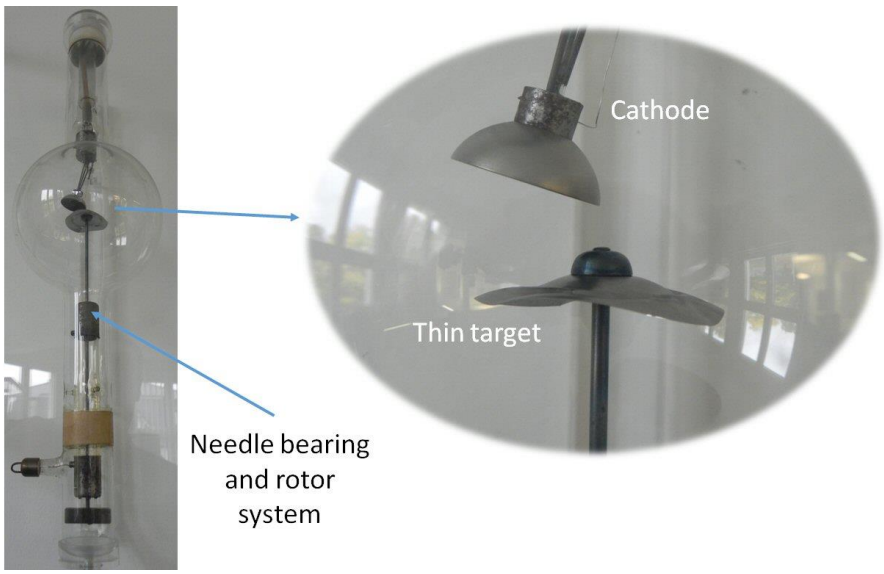

Figure 16 Experimental rotating target tube from 1927 by PhönixRöntgenröhrenfabriken AG, Rudolstadt, Germany, later Siemens. (Picture taken in the Siemens X-ray tube museum Rudolstadt, Germany.)

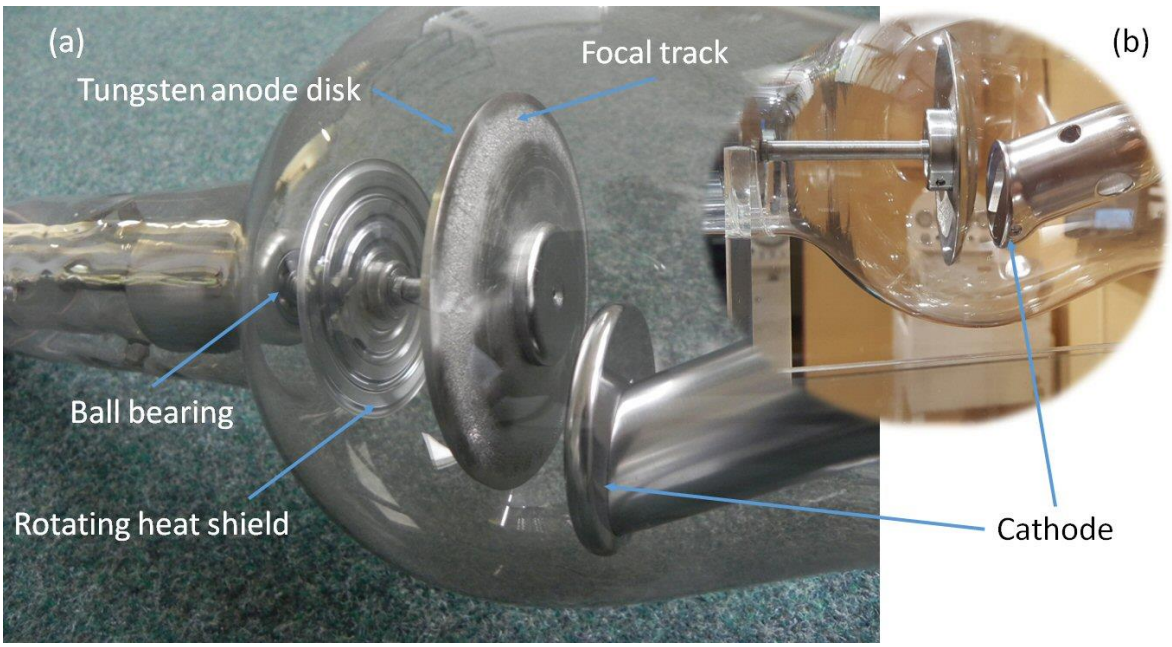

Figure 17 (a) Rotating anode system of a Siemens Pantix™tube, equipped with an all-tungsten high temperature anode disk and produced from 1933 by Siemens-Reiniger-Werke AG, Rudolstadt, Germany. While the Rotalix™ tube primarily stored enthalpy at moderate temperatures in the finned copper / tungsten anode and radiated heatfrom a large surface area, the Pantix™ design aimed at employing the Stephan-Boltzmann ("T^4")law to achieve high heat radiation from a hot disk. (b) Earlier version without a heat shield at the rotating anode. (Picture (a) taken in the Siemens X-ray tube museum Rudolstadt, Germany, (b) taken at the Medizinhistorisches Museum Hamburg, UKE, Germany.)

Figure 18 Siemens Biangulix™ tube. Its anode has two separated focal spot tracks with different anode angles. (Picture taken at the Medizinhistorisches Museum Hamburg, Germany,UKE.)

The benefit of this high temperature concept is high heat dissipation when the anode is at its thermal limit, see **Figure 19** of a Philips tube. Philips used the high temperature concept with the Super Rotalix Ceramics™ tube series, see below in**Figure 51**, delivered from 1980 onwards primarily for angiography and cardiology work, and avoided graphite backing of the all-metal anode, as shown with the Siemens Opti 150 tube in **Figure 20**. But, given the melting point of tungsten, the allowable temperature difference between focal spot and bulk anode of Ungelenk's high temperature tube is lower than with Bouwer's. This reduces the permitted thermal pulse power for comparable focal track speed and focal spot size. To diminish this effect, Siemens enhanced the rotor speed to more than 90 Hz in 1934. 150 or 180 Hz rotor frequency have become standard in the industry since the late 1950's. **Figure 21** depictsa typical current X-ray tube assembly and describes its major components. In 1982 Siemens delivered the Opti 110/12/50 tube with even 280 Hz rotor frequency, used for magnification imaging. However, this high speed is a challenge for ball bearing systems.**Figure 22**illustrates the effect of a bearing failure.

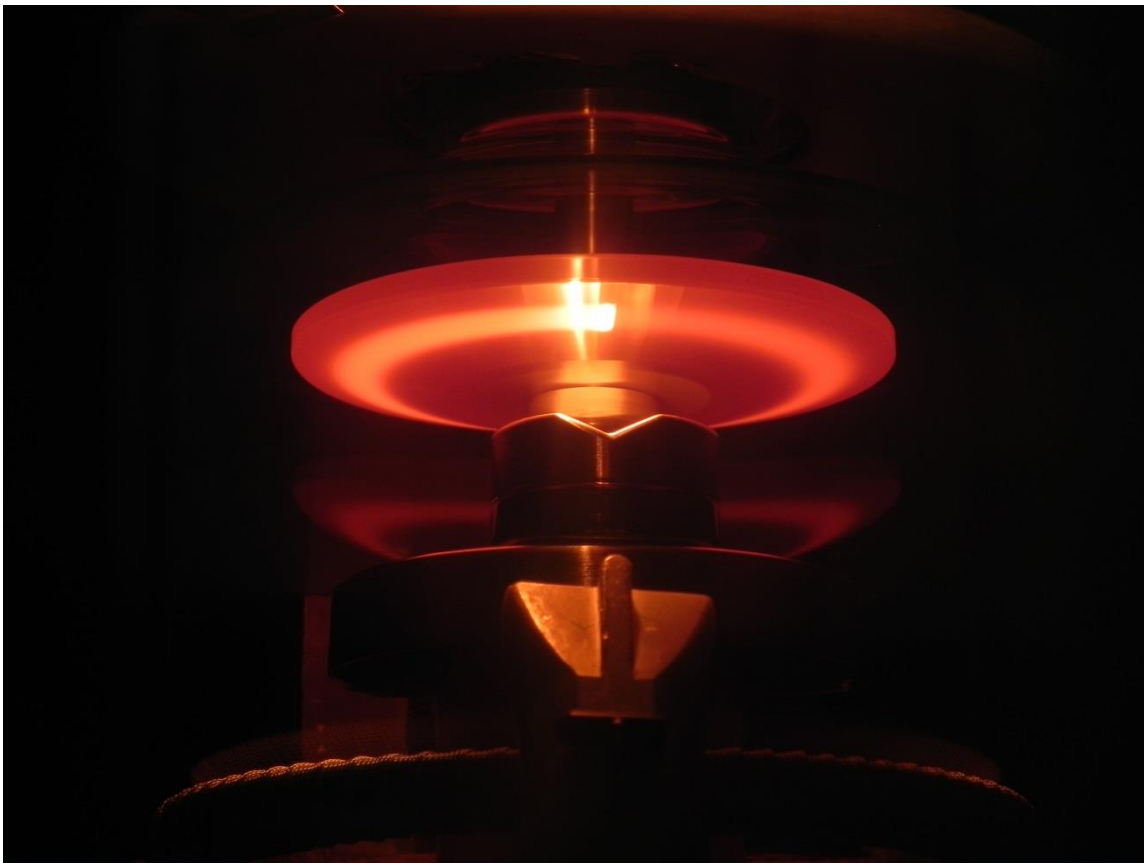

Figure 19 Thermal picture of a rotating anode tube during the exhaust process. The rectangular thermal focal spot and the hot trail of the focal track are visible on top of the light from the filament of the cathode at the bottom, reflected from the anode.

Figure 20 Brazed graphite-backed RW/TZM compound anode in a Siemens Opti 150 30 50 radiographic tube.

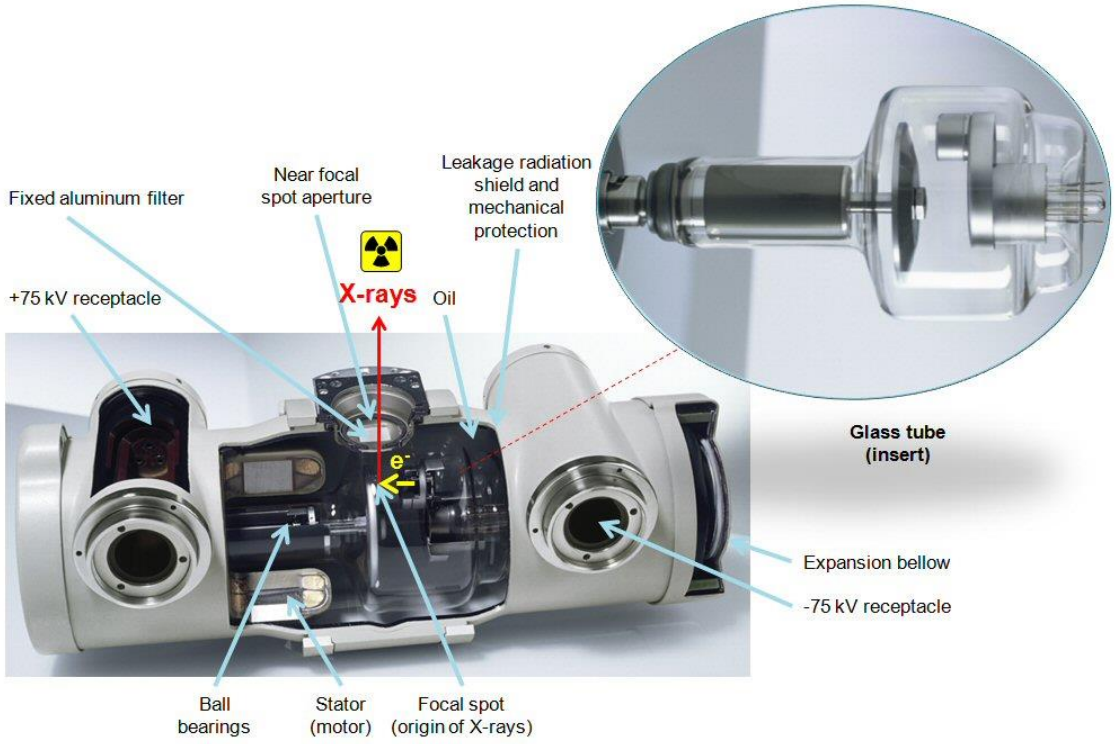

Figure 21 Function and major components of a conventional radiographic X-ray tube assembly from Philips, which has been in production in similar form since the 1950's.

Figure 22 Eroded focal track of a rotating anode. Malfunction of the rotor during two subsequent trials to rotate caused two marks of molten target material (the marks map the shape of the rectangular electronic focal spot).

7. Stationary anode tubes

Since the late 1920's, the concept of rotating anodes, either spinning in vacuum or as part of the tube frame, has become the basis for all modern high performance X-ray tubes. The stationary focal spot remained the thermal weak point, mainly due to the limited heat conduction and heat capacity of tungsten. The industry devised sophisticated cooling mechanisms for the back of the target, like tungsten-in-copper brazed structures and water coolers. In any case, an about one millimeter thick layer of tungsten remained necessary as the first heat spreader. Some attempts were made to cool the tungsten slab directly, but without using hazardous overpressure, steam quenched the dissipation of heat from this hot interface. The gain of performance of stationary anode tubes leveled off over time. However, stationary anode tubes are still important elements of the tube portfolio for surgery C-arm and dental application, where either low and steady photon flux is required, or the system geometry is short enough. **Figure 23**shows the Siemens ERG 80 ö stationary anode tube from 1942, which has the benefit of large long-term heat dissipation through cooling fins. **Figure 24**is a picture of the Philips tube FO 17 with superimposed dual focal spots for surgery C-arm systems and employs a scattered electron trap.**Figure 46** demonstrates a small dental tube for 50 kV tube voltage without such a trap. With such a small tube voltage and current, backscattered electrons may impinge on the glass wall without causing major discharge problems.

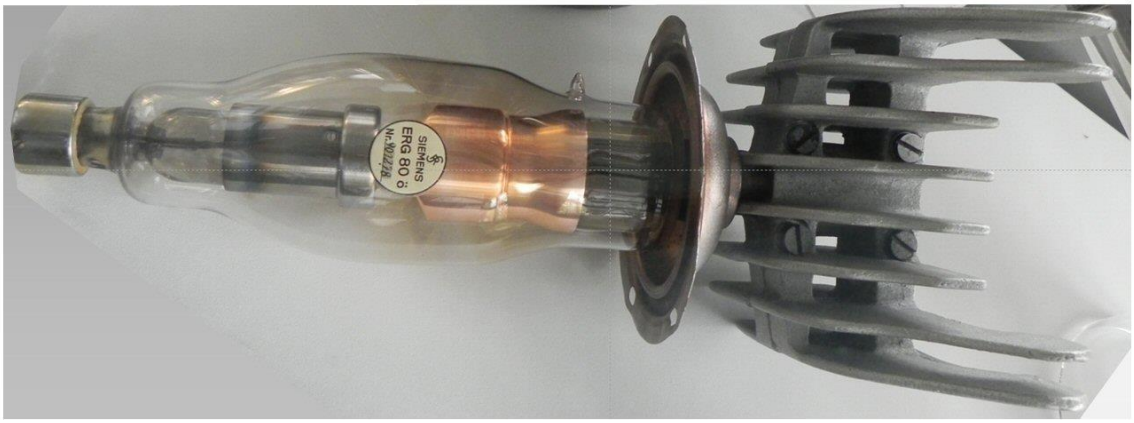

Figure 23 Siemens stationary anode tube ERG 80 ö with cooling fins from 1942. (Photo taken in the Siemens X-ray tube museum Rudolstadt, Germany.)

Figure 24 Close-up photo of the Philips superimposed dual focal spot stationary anode tube FO 17 for surgical C-arm systems.

8. Components development

8.1. Anodes

All-tungsten rotating anodes, first introduced with Siemens' Pantix tube in 1934, lack ductility of the material and are prone to rupture when cold. The high specific mass makes them heavy and brings a large momentum of inertia, a disadvantage when the tube rotor has to start before an exposure. On the other hand, such anodes can be heated to extremely high temperatures beyond 2000°C, and radiate heat well, but require pre-heating to prevent rupture from thermo-mechanical stress. The introduction of specifically lighter molybdenum backed rhenium-tungsten compound anodes in the 1960's was therefore a big step forward. A one millimeter thick top layer of rhenium-tungsten (RT) alloy, backed by an up to several millimeter thick powder sintered titanium-zirconium-molybdenum (TZM) body, has become common and is still the basis technology for most rotating

Anode tubes. Modern tubes often employ segmented rotating anodes to minimize residual strain, see **Figure 38**.

Figure 25 GE-CGR vascular tube with graphite target, coated with tungsten and rhenium.(Photo courtesy of GE.)

From the 1960's, Thomson-CGR, France, later GE, produced a vascular tube with a light weight target, depicted in **Figure 25**. This type of tube was the first in the market to incorporate a rotating anode whose target structure was made principally of graphite. This weight reduction was key to prolonging the life of the ball bearings in vacuum. The great thermal emissivity of graphite is also a beneficial. This first type of graphite anode comprised a coating of tungsten

directly onto a graphite substrate using an electrochemical salt-bath process, with a thin rhenium layer interposed. Later designs were produced through chemical vapor deposition of tungsten from tungsten and rhenium hexafluoride gas.

Philips took a side path and used their high pressure forging facility in Eindhoven, The Netherlands, to produce heavily forged Trinodex™ material, see **Figure 26**. Its benefits are extreme mechanical strength, very low porosity in the top layer and, thus, excellent durability.

For heavy-duty application in angiography, Siemens first and later other vendors introduced graphite-backed RT-TZM, material as depicted in**Figure 20**. Metal center section tubes enabled trapping of backscattered electrons on a stationary structure, primarily close to the X-ray port, see below, **Figures 43**, **Figure 44**. Liquid bearing technology, which emerged in 1990, helped as well to efficiently dissipate heat instead of storing it in the anode.

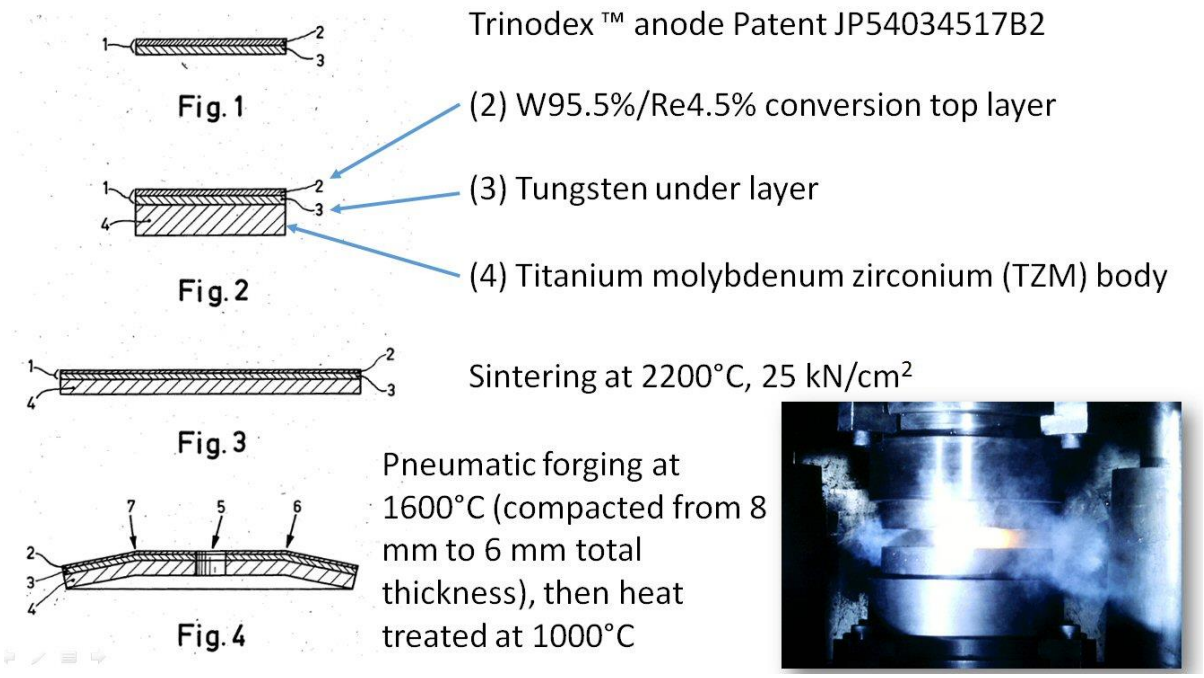

Figure 26 Philips Trinodex™ anode, in production from 1973, hot forged from three metal slabs.

8.2. Cathodes and electron focusing

Improvements of the anode demanded improvements of the cathode. Producers like C.H.F Müller in Hamburg, Germany, improved the spatial image resolution already in the first year after Röntgen's discovery by introducing the so-called "Focus-Tube", similar to the one depicted in **Figure 5**. The metallic cathode plate, which spills out electrons upon ion impact, was given a concave form, such that the negative charge carriers, starting normal to the surface, were focused into a millimeter-sized spot on the anode. The Victor X-ray Company of Chicago, Il (later to be acquired by General Electric to become GEXCO, the forerunner of today's GE Healthcare) used hydrogen as the gaseous species

inside the tube to reduce sputtering effects, and applied a ring-shaped pull electrode in connection with the anode, which enhanced the electron current, see **Figure 27**.

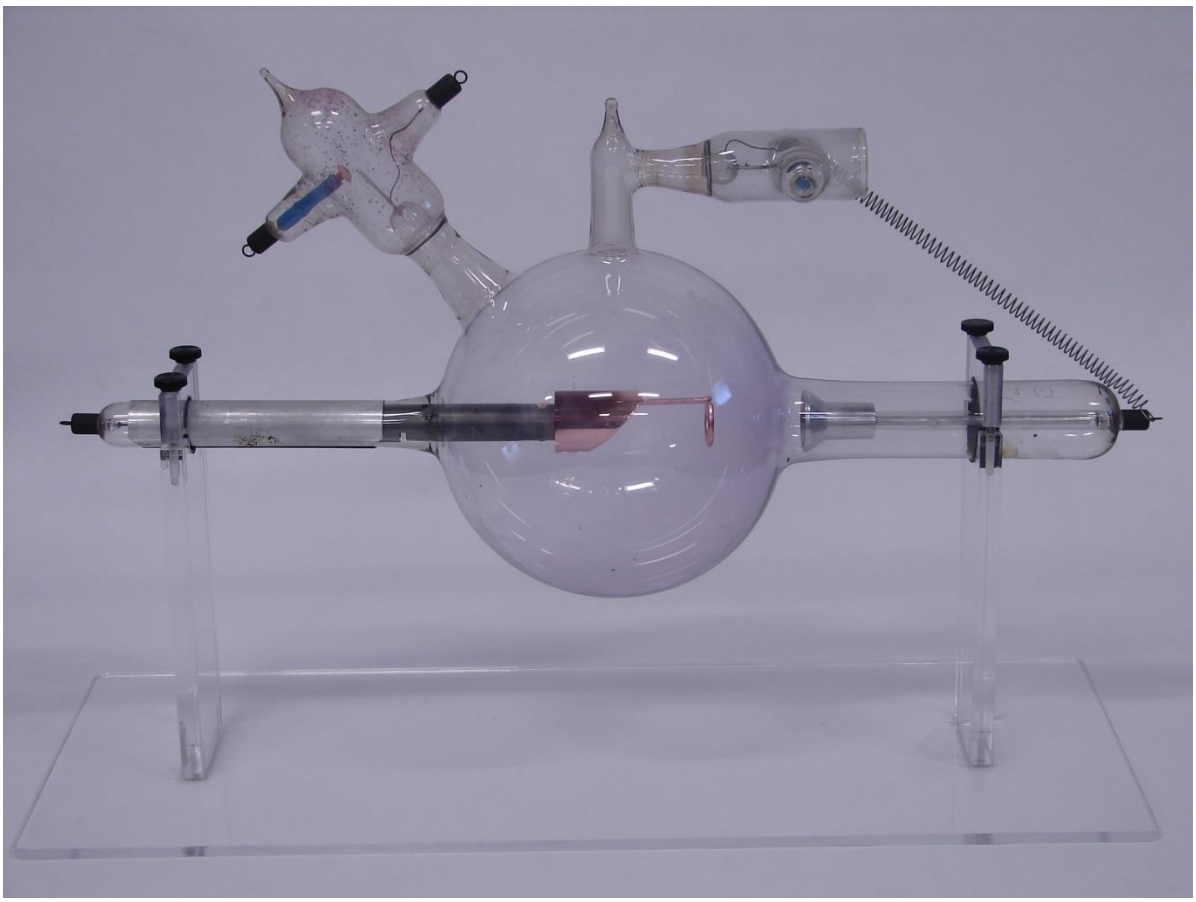

Figure 27 Hydrogen ion X-ray tube with field enhancing pull ring on anode potential, introduced in 1916 by the Victor X-Ray Company of Chicago, IL, later to be acquired by General Electric to become GEXCO, the forerunner of today's GE Healthcare. (Photo courtesy of GE.)

Figure 28 Photo of an original laboratory Coolidge tube, taken on April 30 1913, showing a Wehnelt type focusing ring about the thermionic tungsten emitter. (Photo courtesy of GE.)

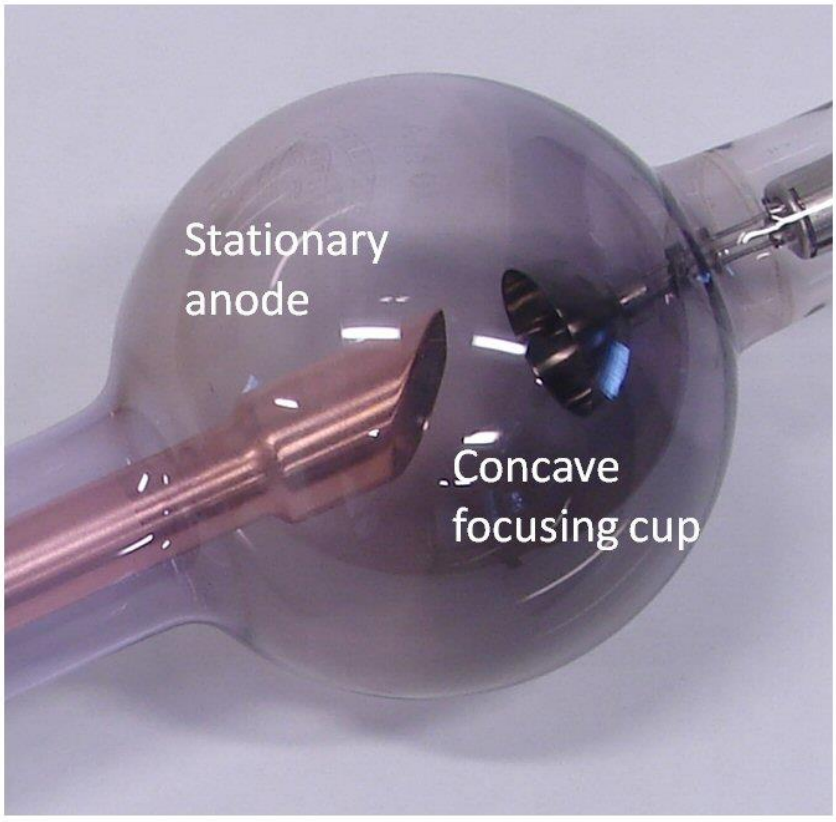

Figure 29 Bell-shaped focusing elements of a stationary anode of a Coolidge tube. (Photo courtesy of GE).

Figure 30 Focusing elements of a stationary anode tube with line focus from C.H.F. Müller, Hamburg, Germany, later Philips. The line focus is mapped in the melting structure on the anode.

After introducing thermionic electron emission, W. Coolidge first encapsulated the tungsten thermionic emitter coil by a small metallic cylinder, as can be seen in **Figure 9** (b). He also experimented with a focusing ring, as depicted in **Figure 28**. In later versions a bell-shaped cathode focused the electrons, see **Figure 29**. Siemens used such a form as well for their first laboratory model of a rotating anode tube, as depicted above in **Figure 16**.

The introduction of line focal spots led to a rectangular shape of the focusing cup, as demonstrated for a tube from C.H.F. Müller (later Philips) in **Figure 30**. The rectangular focal spot can clearly be identified by the erosion pattern on the stationary anode. The classic form emerged by the introduction of larger focusing electrodes to improve the definition of the focal spot even when changing the tube current and tube voltage. Space charge effects, and focal spot "blooming" became apparent, when the anodes allowed for higher tube currents. **Figure 31** shows a tube from the Philips production plant in Eindhoven, The Netherlands, which served to supply the Dutch market during World-War II and shortly after. The cathode head was integrated in a large cathode plate,which shielded the glass insulator from bombardment by backscattered electrons.

Figure 31 Hidden cathode in a Philips tube from the production plant in Eindhoven, The Netherlands. (Picture taken at the Medizinhistorisches Museum Hamburg, Germany,UKE.)

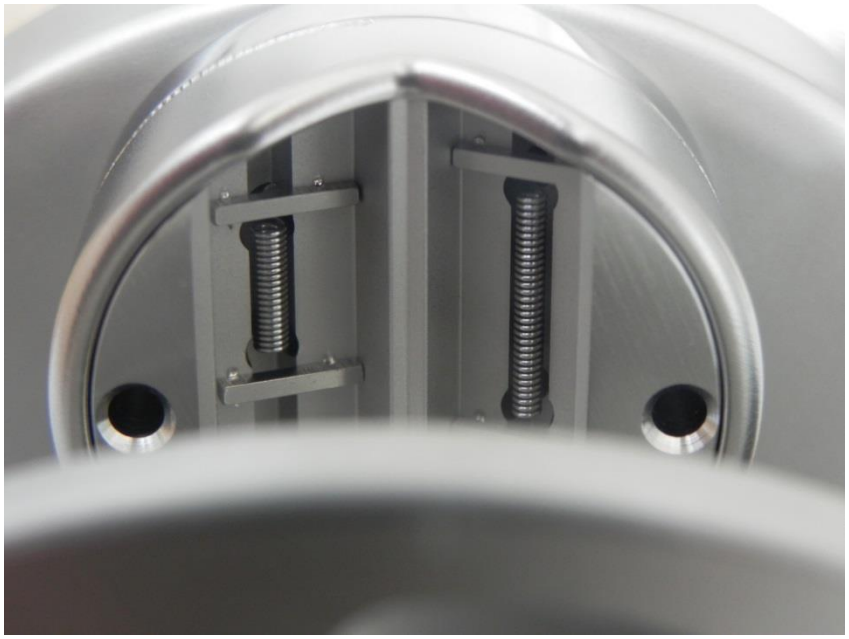

Figure 32 Close-up view of the thermionic cathode for superimposed focal spots of a Philips SRO^{TM} 33 100 tube.

Figure 32 depicts a typical modern dual focal spot cathode for an 80 kW rotating anode tube for radiography. Coiled tungsten wires of 250 µm diameter are mounted into a cathode head which shapes the electric field in such a way that electrons are focused into the focal spot on the anode. The back of its edge can be seen blurred in the front of the picture. On the other hand, space charge effects are electron optically taken into account during design in a such way that the focal spot dimension would not substantially change with tube current and tube voltage. **Figure 52** illustrates the electric

field distribution for a single emitter tube, which leads to a well focused electron beam. Other than with magnetic focusing, electrostatic focusing largely benefits from invariance of the electron trajectories from tube voltage, when the tube current is small and space charge can be ignored. But, due to the relatively high tube current density, space charge effects cannot totally be avoided. In 1998 Siemens introduced a flat tungsten sheet emitter for the Pantix P40 tube for mammography, in 2003 for the Straton™ CT tube, see [25] and [9], and in the Gigalix™ tube series in 2013, see **Figure 54**. Flat emitters improve the starting conditions of electrons, and enable enhancing the electric field, which helps reducing space charge limitations of the emission current. Philips introduced this technology for the iMRC™ CT tube in 2007.

Figure 33 Ball bearing system for Philips SRO™ tube series tube with 90 mm target diameter.

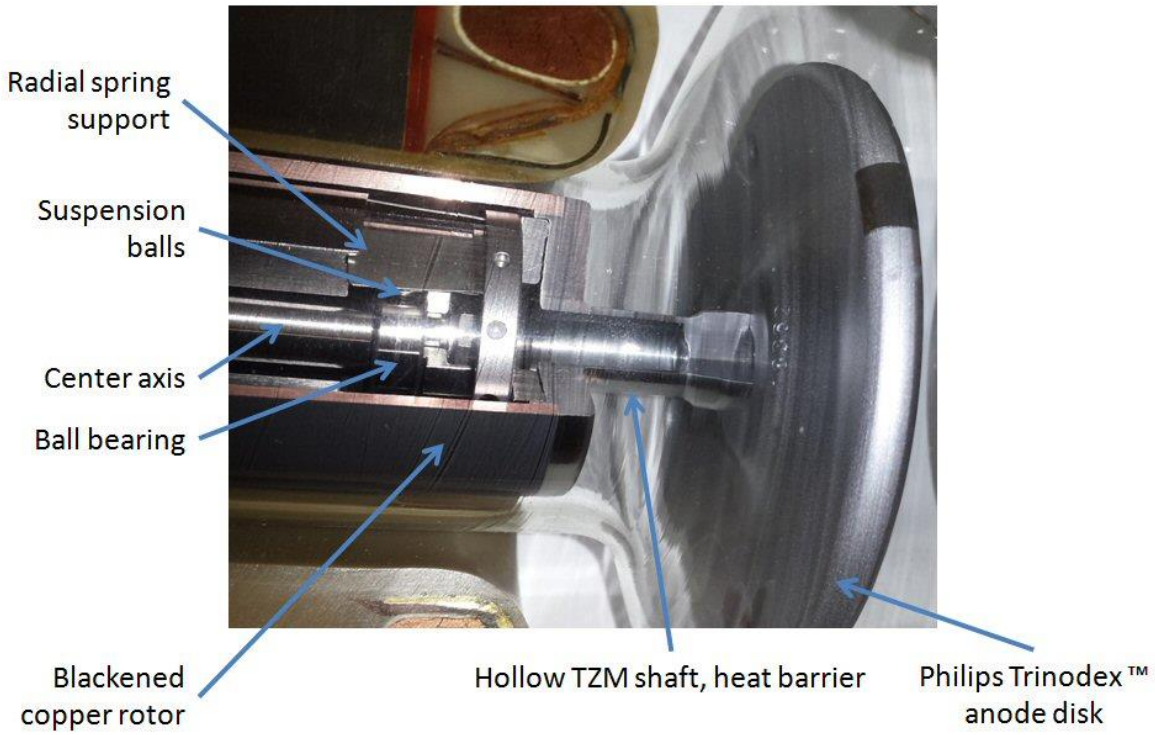

Figure 34 Low noise radial spring supported ball bearing system in a Philips glass tube.

8.3. Bearings and rotor systems

Ball bearing tubes have seen major improvements as well. **Figure 33**shows a ball bearing system for a standard radiographic X-ray tube like the Philips SRO 33100. Since the 1940's, Philips has coated balls and raceways with lead, from 1980 on with silverfor selected tube types. Initially until the middle of the 1990's, lead was rolled-in using a suspension of lead particulates in Vaseline™. Silver was coated galvanic since 1980 for the Super Rotalix Ceramic™ tube, SRC 120, see **Figure 51**. In the 1990's Varian, Salt lake City, USA (now Varex), introduced ion coating, which has become the current standard coating technology.

Philips tackled rotor noise and vibration by implementing a radial spring suspension of one of the individual bearings, which enables the anode rotor to spin nearly force-free about its intrinsic axial axis of inertia, see **Figure 34**. The same principle applied to the straddle-type bearing of the SRC tube shown in **Figure 51**. The center of gravity was suspended between two bearings to even-out the radial load. This concept was later adapted by Siemens for the Akron™ tube series from Siemens in the 1990's, by GE for the Performix CT tube series and by Varian, now Varex, for the MCS 70xx CT tube series.

Still, the rotor life of ball bearing tubes is limited to several hundred hours rotation time. It is therefore essential to stop the rotation after each exposure. **Figure 22** shows the focal spot track of a rotating anode with its typical erosion pattern from thermal cycling. Two melting marks indicate that the tube was damaged by a failure of the rotation system. As an alternative, major vendors, Philips, Siemens and GE tried magnetic bearings. But, controlof the magnetic suspension, and current transfer turned out to be difficult.

Another challenge of all ball and magnetic bearing based concepts is the residual enthalpy, which remains in the anode when the temperature drops and the visible glow of the anode ceases after a patient has been X-rayed, see **Figure 19**. In 1989 Philips returned to the roots of Bouwers and introduced a gallium-indium-tin lubricated spiral groove bearing to keep the rotor cool. This heat conducting liquid metal lubricant allows combining the benefits of great heat conduction of stationary anodes and its flat characteristics of heat dissipation, which is proportional to the temperature difference with ambient, and heat radiation. The invention of the liquid metal bearing for X-ray tubes dates back to the 1970's in the Philips Research laboratory in Eindhoven, The Netherlands. Its market introduction in the Maximus Rotalix Ceramic™ tube (MRC) in 1989 was a quantum leap, see [27]. **Figure 35** shows the assembly process of its bearing system. Cardiology and angiography application benefitted first, before the platform concept has also been introduced for CT. Wait times for the rotor to speed up could be skipped, as the liquid bearing has virtually infinite life time. It may spin all day. Its great heat conduction has accelerated the clinical workflow. Large anodes with high momentum of inertia can be used. The tube runs without any audible noise. **Figure 36**shows a cut-out picture of the first product. In 1987, the author was project manager and R&D manager of Philips' "Röntgenmüller" laboratory in Hamburg, Germany, and the team was frustrated. During tests of the first prototype tube, two years before planned market introduction, the device did not show any sign of generating X-rays at all. The nested liquid bearing was soaked with gas. High voltage could not even be switched on. Eventually, those problems were solved. The MRC^{TM} platform has featured unprecedented durability and continues to be the basis of new developments. Toshiba, Siemens, and GE followed.

Figure 35 Final assembly of a liquid metal bearing system for the Philips MRC^{TM} 200 angiography tube series.

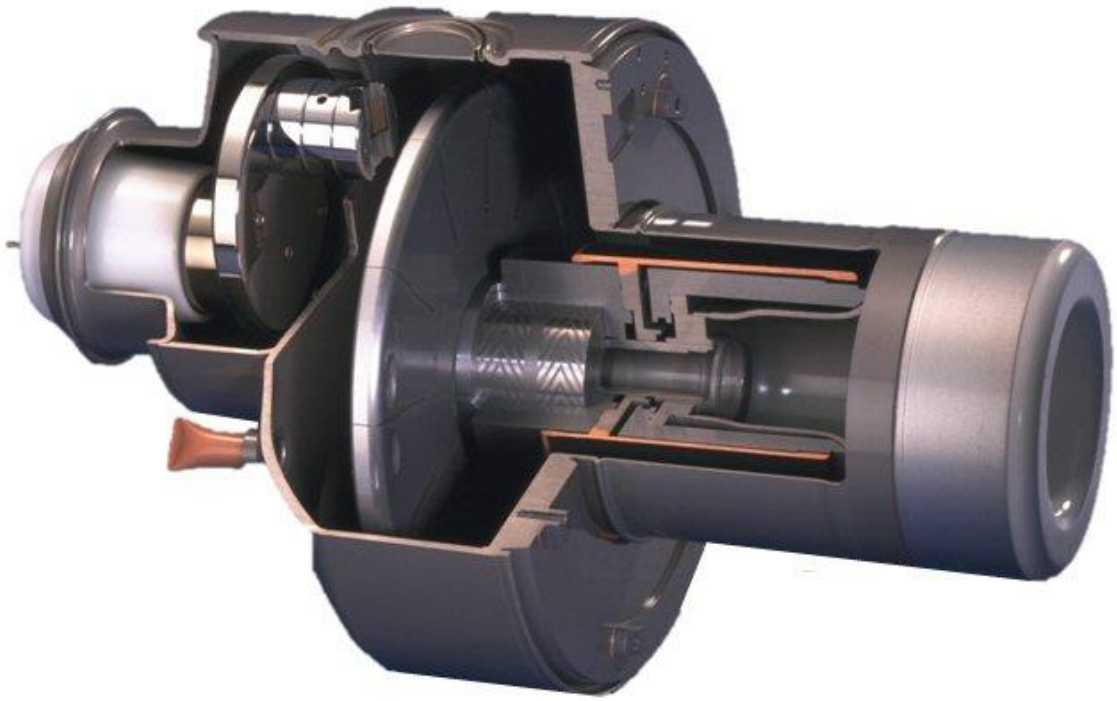

Figure 36 First rotating anode tube with liquid bearing and 200 mm anode disk, Philips MRC^{TM} 200 series for cardiology and angiography.

8.4. Tube frame

i. Glass

Glass envelopes have remained standard technology for low and medium performance diagnostic tubes. **Figure 37** illustratesthe blowing of a glass frame and the tempering process. **Figure 38**is a close-up picture of the X-ray window portion of a conventional glass tube for radiography and fluoroscopy. The near focal spot apertureis visible, which limits off focal radiation and the built-in X-ray filter. Issues with glass insulation arise from the ill-controlled charging by electron and ion impact and coating by metal from the thermionic cathode or from the anode. **Figure 39** illustrates the blue glow of the glass wall caused by electron and ion impact. Some vendors introduced roughened (“frosted”) glass to improve this. **Figure 40** shows a CTtube from Dunlee, Aurora IL, USA, a Philips subsidiary. A special assembly for surgery C-arm systems manufactured by Varian (now Varex), which comprises a glass tube, is shown in **Figure 41**.

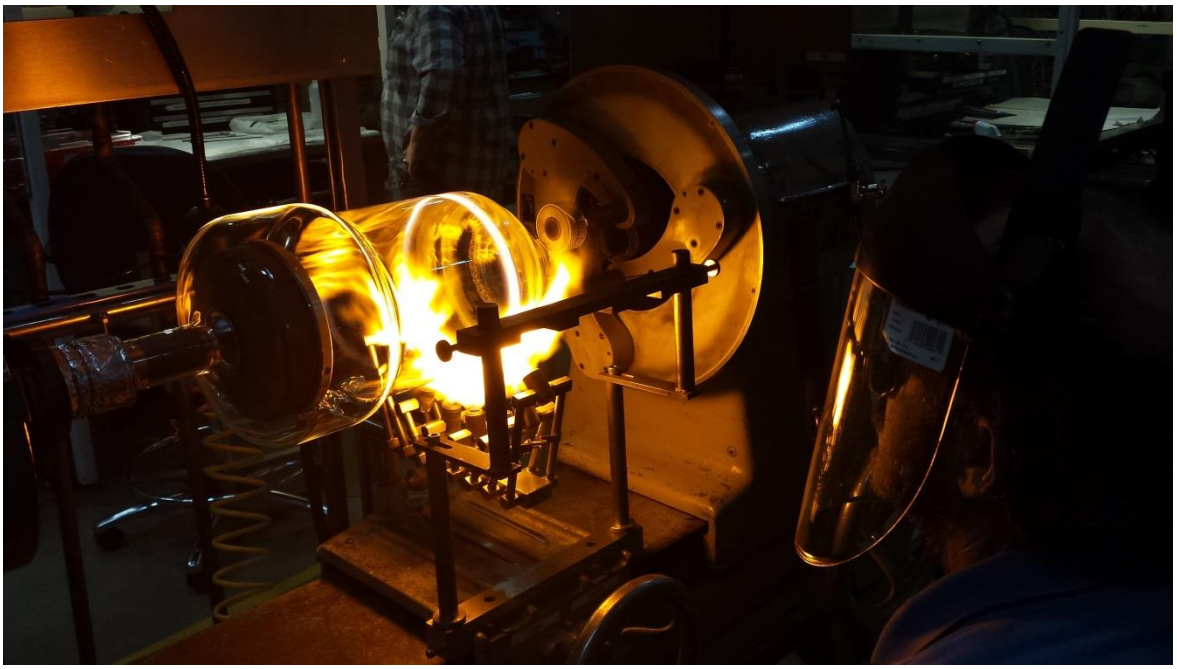

Figure 37 Glass blower at Dunlee, Aurora IL, a Philips company.

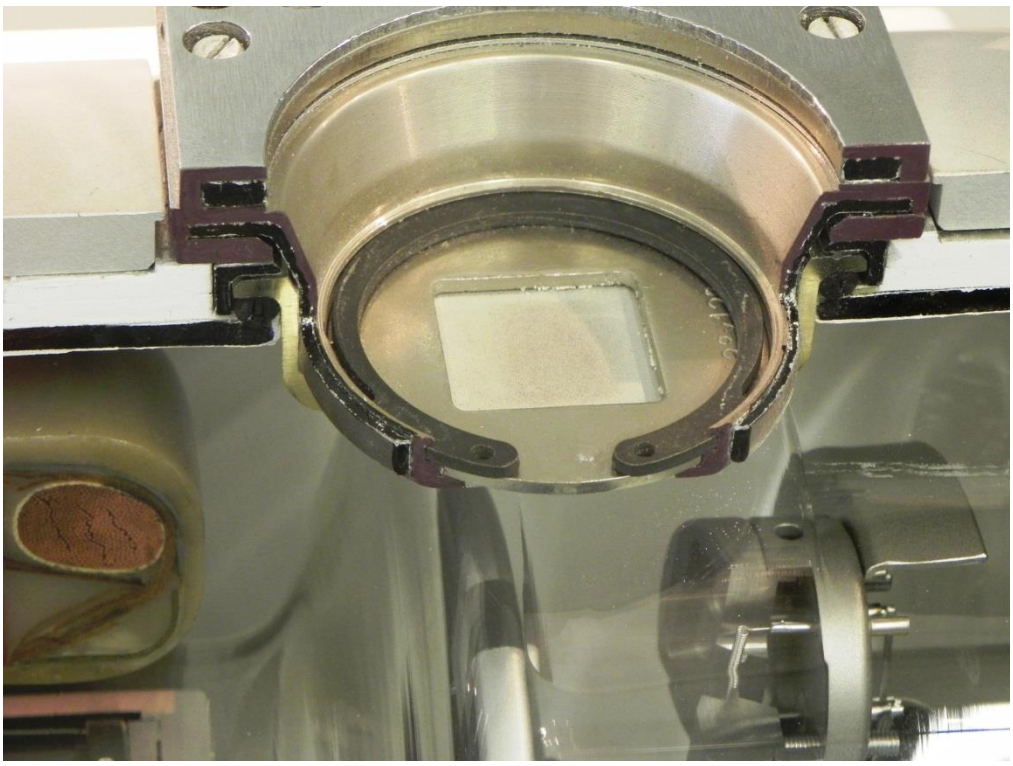

Figure 38 Close-up view of the radiation port of a Philips tube housing assembly for radiography and angiography with exchangeable near focal spot apertureagainst off-focal radiation and intrinsic radiation filter.

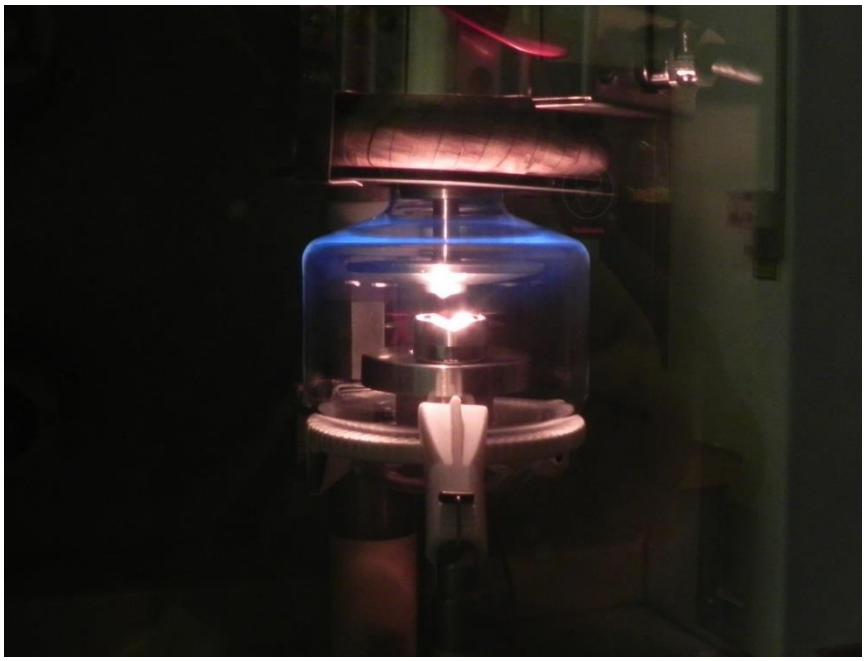

Figure 39 Photo of a glass tube during the exhaust process with electron bombardment of the anode. The blue glow at the inner glass wall (top, about the cathode region) signalscontinued impact of backscattered electrons and ionson the glass.

Figure 40 Frosted glass wall of a tube from Dunlee, Aurora, IL, USA, subsidiary of Philips, to improve the electrical stability under bombardment by backscattered electrons.

Figure 41 Varex tube OR-III tube assembly with RAD-99 glass insert for surgical C-arm systems. (Picture courtesy of Varex.)

ii. Metal center section

Bouwers from Philips had already implemented a metal center section in a stationary anode tube Metalix™ in the 1920's, and re-used this X-ray shielding and protection technology for the first rotating anode tube Rotalix™ in 1929, see **Figure 12 (d)** and **Figure 12 (e)** above.**Figure 42**shows a GE tube MX-125 for angiography from 1972; and **Figure 43** depicts the details of glass-metal joints and the beryllium X-ray window of the Philips Super Rotalix Metal^{TM} tube series, launched in the late 1970's. As the metal center section of a bi-polar tube is subject to bombardment of scattered electrons from the focal spot, special attention has to be payed to thermal management of the X-ray window area and the unbalance between cathode and anode current. **Figure 44** illustrates the thermal fingerprint at the X-ray port of bi-polar angiography tube. Cooling oil cracked where temperatures of the frame (from of impact of backscattered electrons) exceeded ca. 200°C during operation.

In the 1950's, glass tubes for non-destructive testing had become available for tube voltages of more than 250 kV. The assemblies were bulky and difficult to handle. Starting in the late 1970's, Philips Hamburg, Germany succeeded replacing glass for high performance stationary anode tubes by compact metal frames with ceramics insulators, see [28]. A cut-out model of the first metal-ceramics tube on the market, the Philips Super Rotalix Ceramic SRC^{TM} 120 0612, is depicted in **Figure 51**. This design initially caused severe problems by effects of surface flashover and puncture of the ceramics insulators when high currents were applied. Vacuum ultraviolet radiation, X-rays, ions and scattered electrons destabilized the isolating capabilities. Proper shielding of electrical triple points, improved processing and better ceramics solved the issues. Typical traces of tube arcing in a metal center section tube are well visible in **Figure 45**. Despite of these rough conditions the metal electrodes survive. Eventually, a novel robust technology of all metal ceramics tubes emerged, which is well received, notably in the US market.

In addition to the tube housing, metal center section technology also enables a high degree of recycling of vacuum components. The SRC™ tube and its successors, notably the Philips MRC™ tube series with liquid bearing, see **Figure 36**, can be disassembled and re-sealed multiple times. Begining with the SRC tube, metal ceramics technology has been introduced by all major vendors of high-performance tubes.

Figure 42 GE MX-125 metal center section tube for the emerging angiography application, introduced in 1972. (Photo courtesy of GE.)

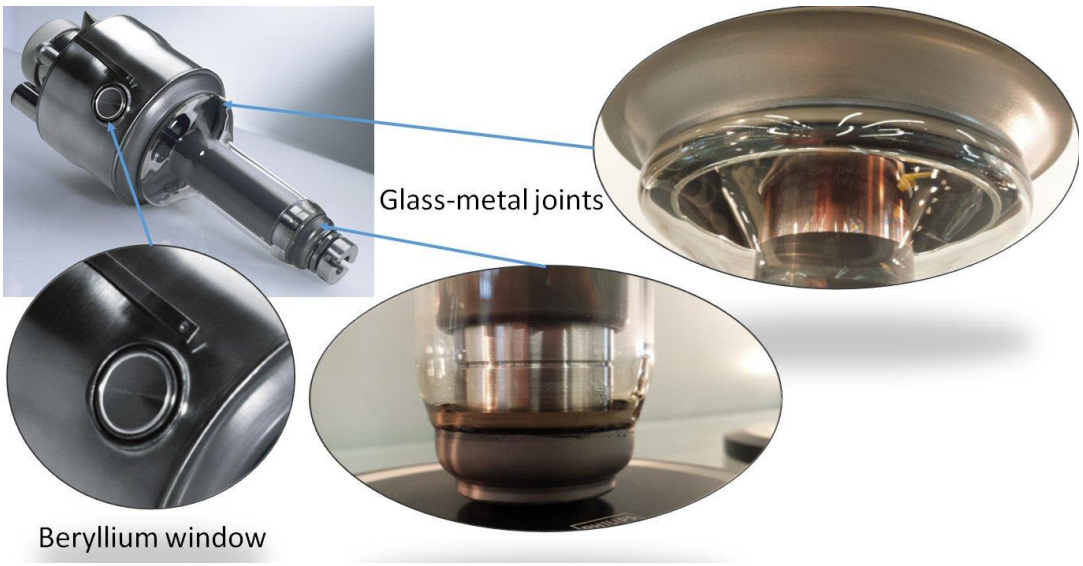

Figure 43 Philips metal center section tube technology with steel frame, alumina coated beryllium X-ray window and glass-metal joints.

Figure 44 Carbonized beryllium X-ray window after impact of electrons backscattered from the focal spot of a bi-polar angiography tube.

Figure 45 Traces of arcing between metal electrodes of a metal center section tube for angiography. A glass wall would have imploded under such severe arcing.

9. Special applications and features

9.1. Dental X-ray

In dental systems, the small distance between X-ray source and image receiver allows for low tube voltages and low power ratings in single-shot dental application. **Figure 46** depicts a simple stationary tube for 50 kV tube voltage. **Figure 47**shows a cut-off picture of a Philips Oralix^{TM} dental tube housing assembly including high voltage transformer and rectifying circuitry. The tube comprised a kind of Wehnelt electrode, which consists of a cathode plate which is isolated from the electron emitter coil. Tube current and focal spot size were stabilized using self-controlled resistive biasing. The tube current is being fed into the electron emitter by means of a resistor, whereas the focusing electrode is directly connected to the negative high voltage terminal This produces negative bias (with respect to the electron emitter) at the focusing electrode. As a result, the focal spot width is reduced and the electron emission self-stabilized.

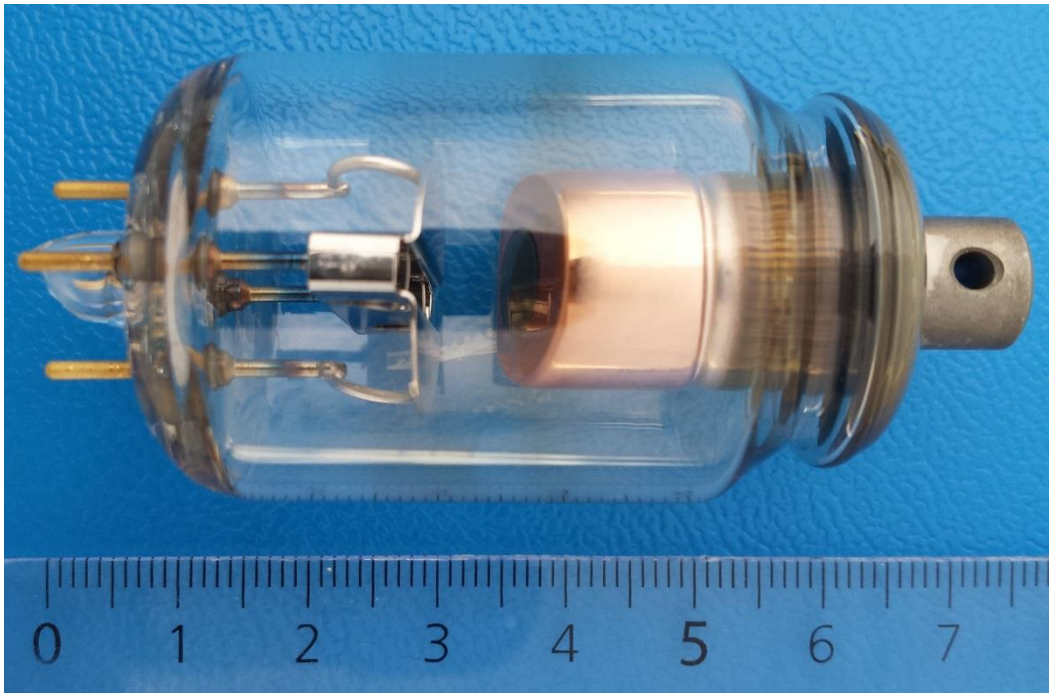

Figure 46 Philips dental tube FO12 for the Oralix^{TM} tube head, shown in Figure 36b, and centimeter ruler.

Figure 47 Cut-off picture of a Philips Oralix^{TM}dental tube head. Tube current and focal spot size were stabilized with a Wehnelt electrode and self-controlled resistive biasing. (Picture taken at the Medizinhistorisches Museum Hamburg, Germany,UKE.)

9.2. Mammography

Despite of being more costly than all-glass frame technology, metal center sections, which employed an X-ray window from beryllium, helped reducing X-ray attenuation and filter strength for the soft radiation required for mammography application. **Figure 48** depicts a cathode-grounded mammography tube, produced between 1980 and 1991 by VEB Röhrenwerk, Rudolstadt (Rörix), GDR, now Siemens. Although glass technology served well from a thermal and high voltage perspective for tube voltages between 18 kV and 50 kV, a glass frame causes undesired hard X-ray filtration. In the beginning of mammography glass tubes were indeed being used. But, it became clear very soon, that softer radiation was required for an optimal contrast-to-noise ratio in the images of soft tissue with potentially embedded malign calcifications. First, X-ray windows from beryllium were attached to the glass frame, and molybdenum or rhodium k-edge filters were added. **Figure 48**shows a better solution. Except for the necessary insulation by glass, the entire tube frame was made of metal. A beryllium window with low attenuation and X-ray filtration was brazed-in. The cathode of the tube was grounded. This simplifies “biasing”the cathode to minimize the focal spot width. Instead, CGR, France, a GE company, introduced an anode grounded solution in 1992.**Figure 49**shows a cut-out model of the tube housing assembly with the Statorix 52.2 (DMR) tube, produced from 1992. The tube has two comparatively large focal tracks, coated with rhodium and molybdenum, and positioned on the perimeter of the anode. It delivers minimal off-focal radiation and allows for convenient patient positioning.

According to the records of Varex, Salt Lake City, UT, USA, mammography tubes were the first X-ray sources which the predecessor company Varian produced, see **Figure 50**.

Figure 48 Mammography tube with metal center section, cathode grounded, produced between 1980 and 1991 by VEB Rudolstadt (Rörix, later Siemens), Rudolstadt, GDR.(Photo taken in the Siemens X-ray tube museum Rudolstadt, Germany.)

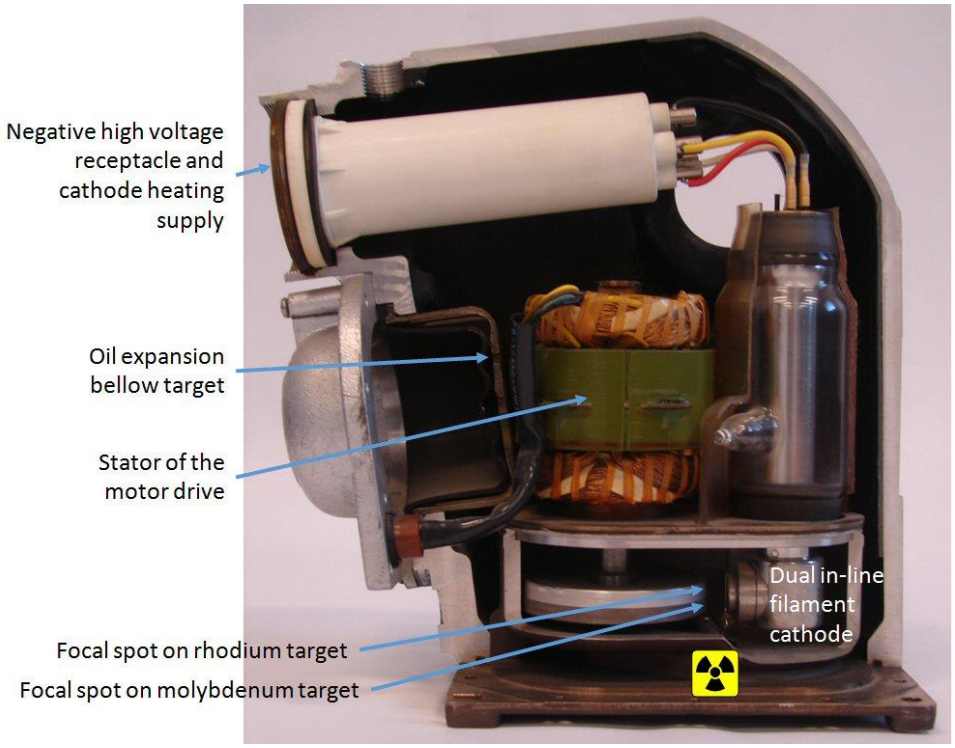

Figure 49 GE DMR mammography tube assembly. X-ray focal spots on molybdenum and rhodium targets positioned at the perimeter of the anode. (Photo courtesy of GE.)

Figure 50 The first tube produced by Varian, Salt Lake City, UT, USA (later Varex), the mammography tube B113 with metal center section, cathode grounded. (Picture courtesy of Varex.)

9.3. Angiography / cardiology application

Increasing fluoroscopy application in the 1970's, and the necessityto record sequences of images in cardiology and angiography procedures (instead of single exposures), exceeded the technical capability of the glass tubes at the time. Tube life was inacceptable; the limited thermal energy per patient, which the tubes could sustain, was inappropriate and hampered the image quality and the work flow. The introduction of a graphite target by GE, see **Figure 25**, at least minimized the starting time and improved the durability of the balls bearings during long runs of an angiographic procedure.

Figure 51 First all-metal-ceramics rotating anode tube in the market, introduced in 1980 by Philips, pioneering all high performance tubes of major vendors. ThisSRC ™tube series featureda comparatively large high temperature Trinodex™ anode (at that time), compact design, scattered electron trap, rotating anode insulator to minimize the air-gap of the motor for short start-up time, silver-coated straddle ball bearing system with radial spring bearing suspension and axial pre-load thrust spring.

Philips improved the situation by introducing the full metal ceramic tube Super Rotalix Ceramic™ tube SRC 120 0610, see **Figure 51**, which featured a relatively large anode, suspended on a radially spring-supported straddle bearing system with a rotating ceramics insulator to maximize the efficiency of the motor. High patient and staff dose associated with angiographic diagnostics and therapy on site demanded for counter measures. One of them is enhancing X-ray filtration to narrow the spectrum. A powerful tube like the MRC™ is required to benefit from hard filtration without introducing image noise and waiting times for cooling.

Another major step forward was the introduction of a tube current switch that operated without changing the tube voltage. Philips introduced it for angiography and cardiology tubes of the MRC™ series in 1992, in 1996 with the MRM™ tube series, and later also with SRM™ metal center section tubes in radiography/fluoroscopy systems as grid controlled fluoroscopy GCF™. Already in 1937, Siemens had introduced grid control of the electron emission, similar to the current modulation in radio valves.

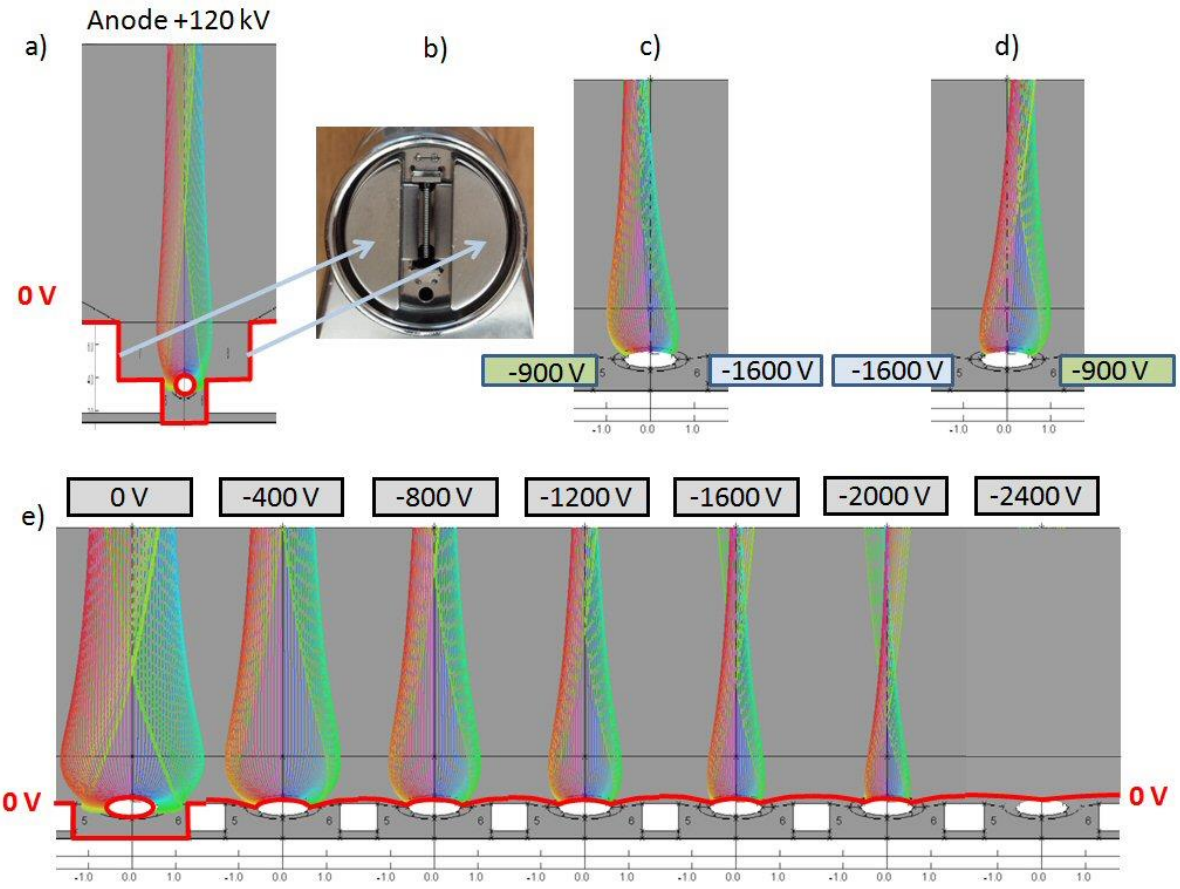

Figure 52 Ray tracing of electrons. Planar cross section through the emitter coil. Biasing of the control electrodes allow for focal spot deflection, as used in CT application, and also for switching the electron beam off.

Figure 52 demonstrates the basic principle of electron beam focusing, biasing and switching off the emission of electrons. Charging the electrodes, which surround the thermionic emitter,with a negative cut-off potential quenches the electron emission. The electron emitter is isolated from the rest of the cathode head. Upon application of the negative bias, the equipotential line, which represents the potential of the electron emitter, shifts allowing only electrons which still experience a pulling electric field (and which emerge from areas close to the center of the cathode coil) to escape. At cut-off the entire emitter is "covered" by a repelling field. Usually, the focal spot size shrinks with growing absolute bias, which allows for controlling the image resolution electronically. Further, in **Figure 52,** a means for deflection of the electron beam is shown, as used in many X-ray sources for CT. **Figure 53**shows the grid switch box, which Philips has been integrating in similar form into the tube housing assembly of the MRC tube series for angiography and cardiology from 1993 onwards. Other manufacturers have at least temporarily realized this feature with bias supply from the high-voltage generator, like Toshiba, and Siemens with early Megalix™ tubes and the latest angiography tube series Gigalix™. This tube, shown in **Figure 54**,comes with "gridded" flat electron emitters and a liquid bearing.

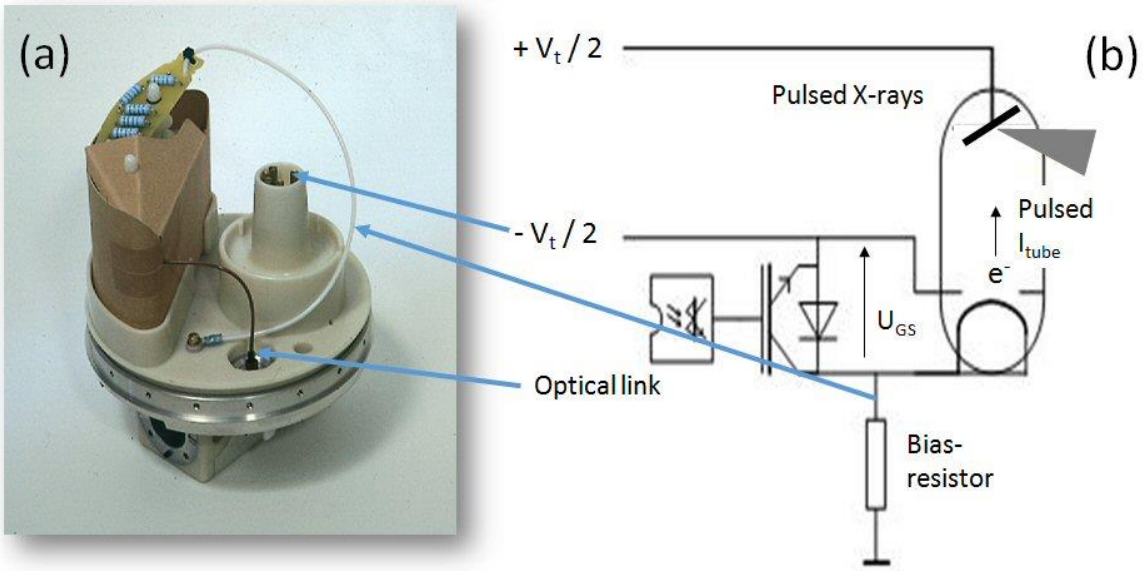

Figure 53 (a) Grid switching electronics for Philips angiography tubes, integrated in the tube housing assembly of the MRC^{TM}tube line, see **Figure 28**. (b) Electric schematics: The tube voltage remains unchanged when, upon an optical signal, the tube current I_{tube} is stalled by applying a negative voltage U_{GS} of several kilovolts between isolated cathode head and tungsten emitter. As the spectrum does not change, this "gridding" avoids unwanted soft photons during pulsing of the X-ray flux.

Figure 54 Siemens angiography tube of the Gigalix^{TM}series, launched 2013, with grid switchable flat electron emitter and liquid bearing. (Picture courtesy of Siemens.)

9.4. Compactness in radiography

The quest for compactness, versatility and scalability has inspired Varex, Salt Lake City, UT, USA to offer a series of single polar "anode end grounded" (AEG) tubes since 2010. **Figure 55 s**hows the drawing of a mammography tube type from patent literature. Rotating anode and X-ray focal spot are on ground potential, positioned proximal to one end of the tube housing assembly. The cathode is charged with negative high voltage potential. A stationary electron trap collects back-scattered electrons from the focal spot and reduces the electrical power supplied to the rotating anode. The

small insulating gap keeps the efficiency of the motor drive up. Its magnetic stator is positioned parallel with the cathode.

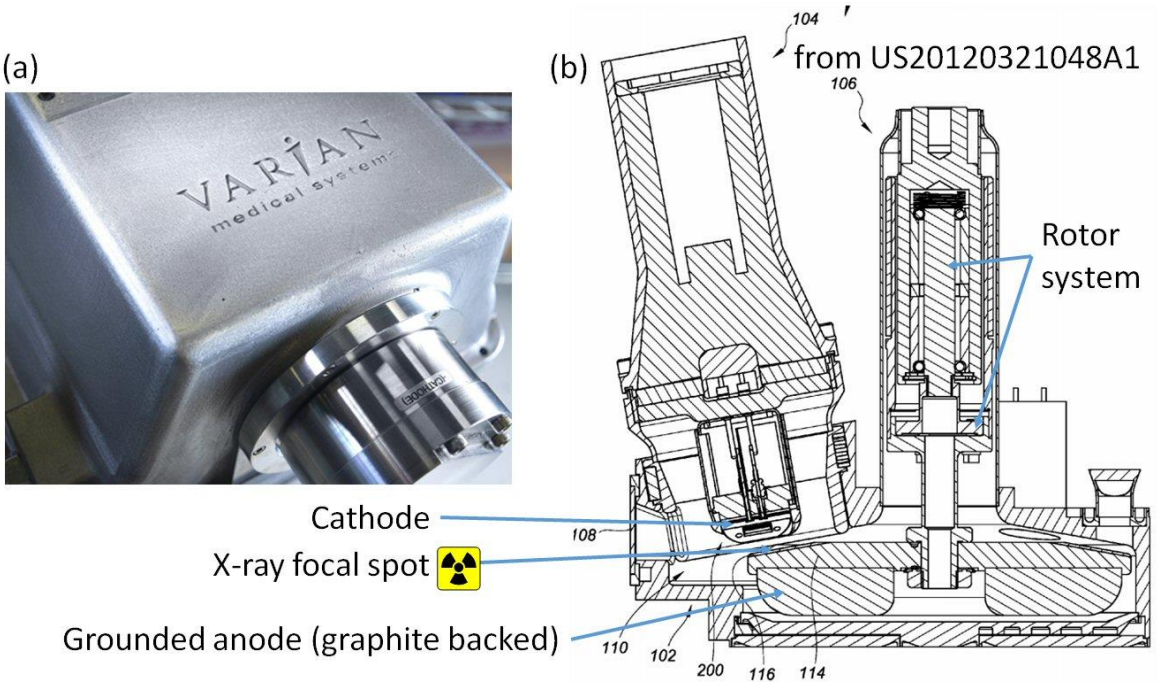

Figure 55 (a) Logo on one of the first anode end grounded (AEG) tubes developed by Varian, now Varex, Salt Lake City, UT, USA. (b) Drawing of an AEG tube frompatent application US20120321048A1. (Picture (a) courtesy of Varex.)

10. Production

Electrical stability and mechanical precision of X-ray tubes under high voltage of up to 150 kV and temperatures of up to 3300°C in the focal spot can only be guaranteed by well-controlled and clean production. Over decades, production yield at major manufacturers were in the range of 50% to 90%. Meanwhile, stringent process improvement and high quality material supply, rugged design, and high investment in production technology resulted in reduction of the scrap rates by at least an order of magnitude. **Figure 56** illustrates the evolution of production environment over nearly a century.

The development of the X-ray tubes continues, as an essential component of medical diagnostic imaging.

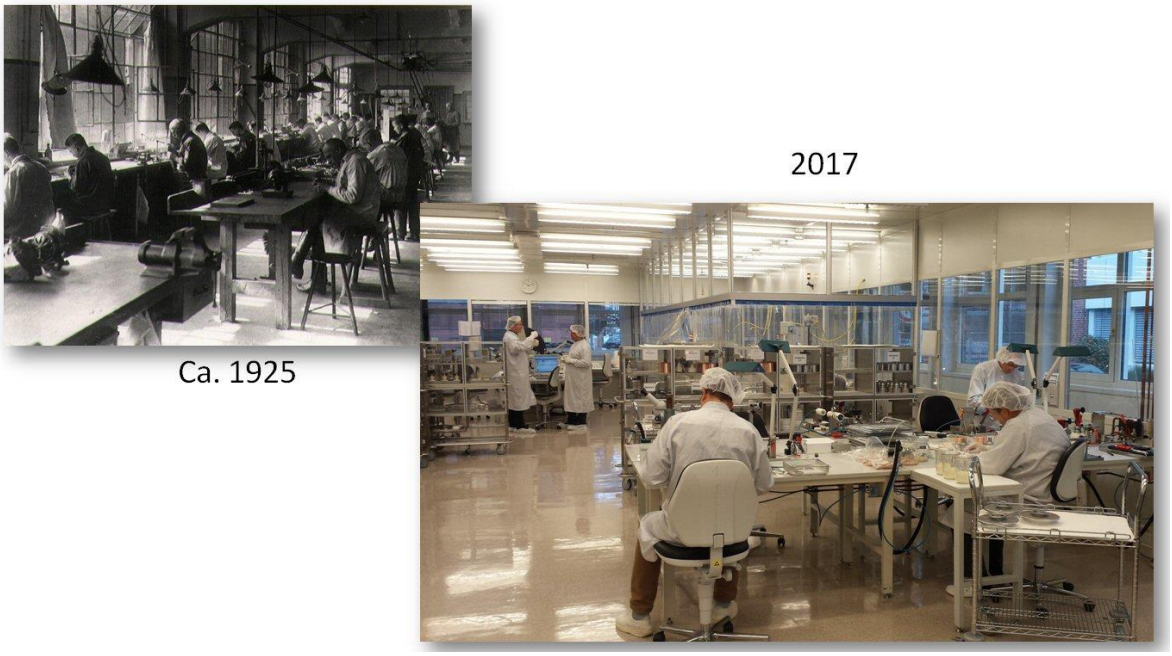

Figure 56 Assembly rooms at C.H.F. Müller, Hamburg, Germany, later Philips, around the year 1925, andin 2017 at the PhilipsX-ray tube plant in Hamburg. (Picture courtesy of Philips.)

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FILM-SCREEN RADIOGRAPHY RECEPTOR DEVELOPMENT

A HISTORICAL PERSPECTIVE

Perry Sprawls, Ph.D.

Content

1. Introduction and Overview

Radiographic receptors in which the image is recorded and displayed on photographic type film were used for more than a century after the introduction of x-ray imaging of the human body in 1895 by the physicist, Wilhelm Roentgen. Over this period of time there have been many innovations and developments in the design of the technology and clinical applications establishing radiography and other forms of x-ray imaging as a major medical procedure. With x-ray imaging being a physical process it has provided an opportunity for physicists to be major contributors in research and development along with providing scientific support for effective and safe clinical procedures. This provided a foundation for medical physics to develop as a major and highly-respected professionwith academic programs and degrees at universities and certification by professional organizations.

The history of screen-film radiography development is extensively documented and published in the many scientific papers on the various developments, textbooks of the period, and especially many historical review books and articles, often published on anniversaries of significant events. A selection of some of the most significant publications documenting the history is included in the bibliography at the end of this chapter. It is not our purpose to repeat what has already been extensively published. Our plan here is to develop an understanding of the issues that were the motivations for the research and developments that provided the historical foundation.

Over a century of research and development on film-based radiographicreceptors has produced greatly extended visibility within the human body with the lowest possible radiation exposure. That is what we will now explore beginning with some basic background.

Medical radiography is the process of producing fixed or recorded images of the internal structures, functions, and signs of disease or injury within the human body using x-radiation. Technology for the production of radiographs consists of two major components as illustrated in Figure 1: a source of the x-radiation consisting of an x-ray tube and associated electrical energy sources, located on one side of the body, and the image receptor located on the other. The historical development of x-ray tubes and related equipment is described in other chapters. Here we consider the receptor introduced in Figure 1.

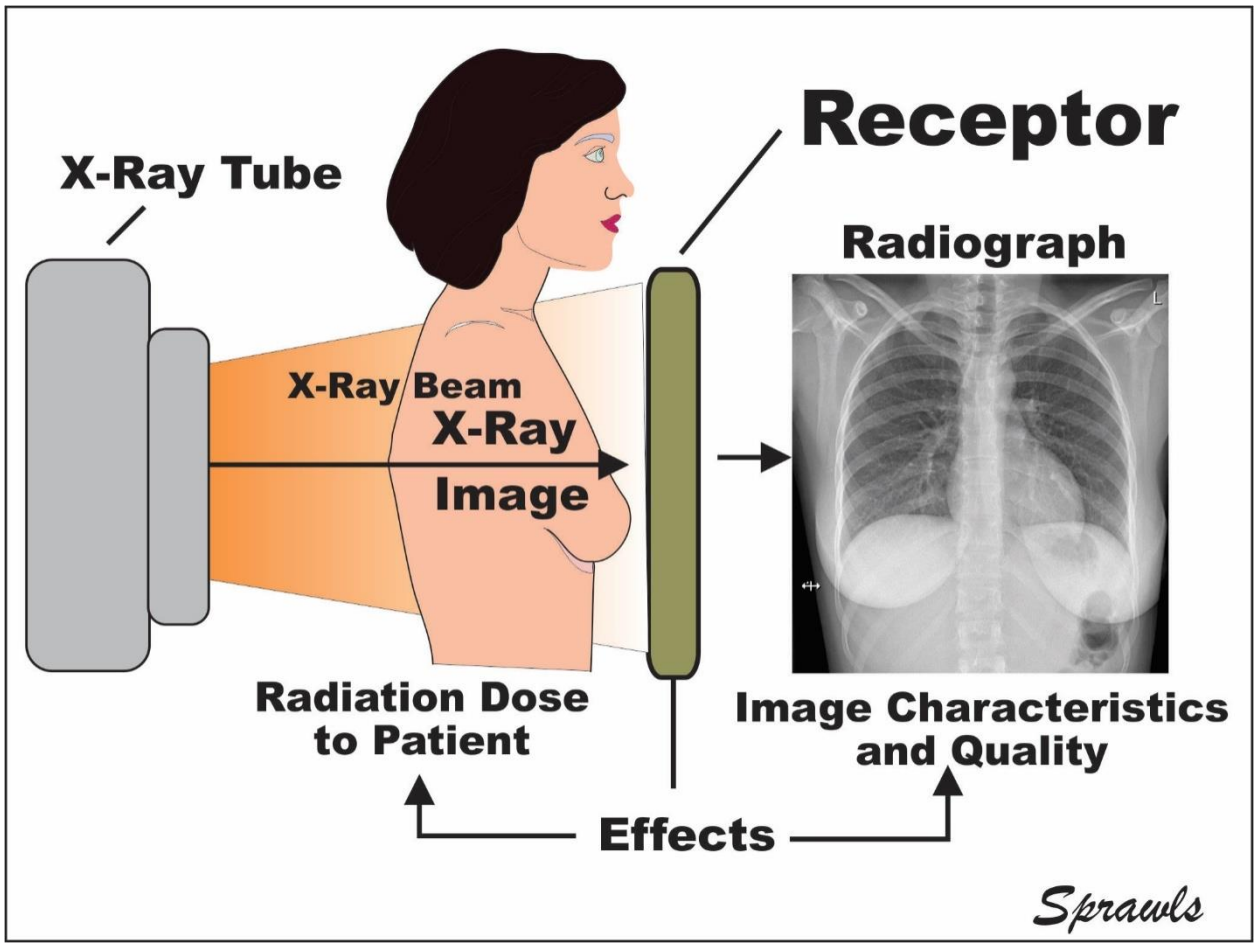

Figure 1. The general function of a radiographic receptor and the effects that are determined by design characteristics.

The receptor is the component that "receives" the invisible x-ray image coming from the patient's body,known as the latent image and converts it into a visible image.

Over the course of history there have been two very distinct and different types of receptors. The first, which was used for over a century, was based on a chemical process that formed images on sheets of photographic type film in contact with fluorescent screens and generally designated as *film-screen radiography*. The second was a physical method using digital electronic technology and designated as *digital radiography*.

In this chapter we trace the development of film-screen radiography from its origin with Roentgen's discovery, research, and demonstrations up to and including the science and technology associated with the final design characteristics at the time film-screen was replaced with digital technology. An overview of this evolution is shown in Figure 2.

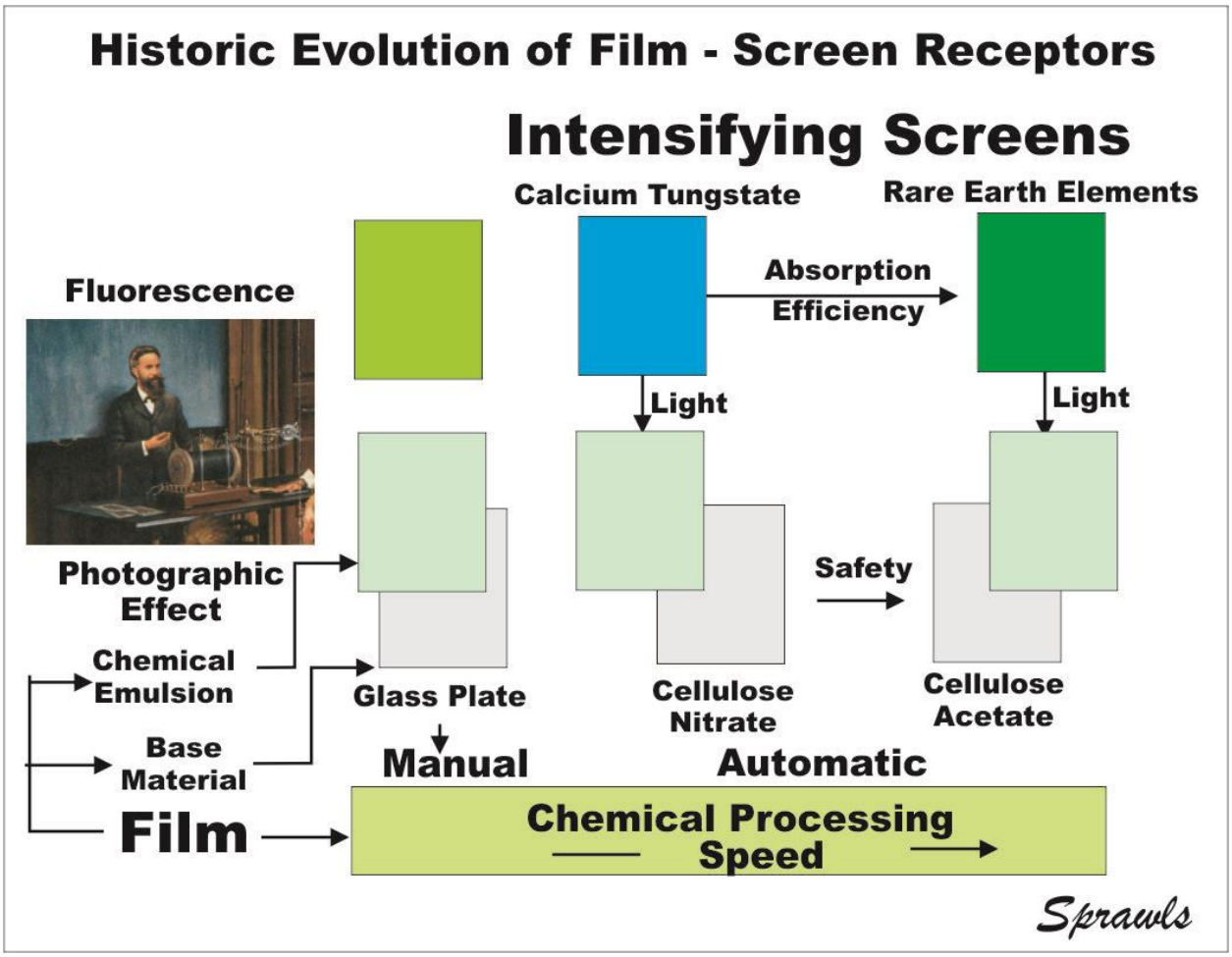

Figure 2. The major phases in the development and evolution of film-screen radiographic receptors.

The introduction of medical radiography to the world came when Roentgen gave a presentation describing his research finding on the characteristics of "a new kind of radiation" and demonstrated the process of imaging internal structures of the human body at the University of Würzburg on January 23, 1896. The news spread rapidly around the world and the process was repeated in many locations, usually in physics laboratories that already had the equipment for generating x-radiation (partially evaluated glass tubes and high-voltage electrical sources) that was being used for other purposes.

Photography was an established technology at this time and photographic plates were the available receptors.

Roentgen discovered and investigated two properties of the new radiation that were to be the foundation of radiographic receptors for well over a century. This was the radiation produced light in certain fluorescent materials, or phosphors, and also could form images in photographic materials. It is actually the combination of these two effects that produces radiographic images within a receptor and will be reviewed throughout this chapter.

The continuing research and development contributing to the evolution of film-screen receptors was driven by at least three factors:

- *Increased Image Quality* was a major factor to expand the scope of anatomical structures and pathologic conditions within the human body that could be visualized. This continued to increase the clinical effectiveness of radiography as a diagnostic method.
- *Reduced X-ray Exposure* to patients. This is an ongoing challenge because several elements of image quality depend on the quantity of radiation used. A significant effort in receptor development has been to increase the efficiency, or "quality-to-exposure" relationship.
- *Increased Efficiency and Productivity.* Images recorded on large sheets of film required considerable effort and labor in handling and especially storage and retrieval (archiving). Chemical processing of film consumed both staff time and effort and added a significant expense to the imaging process. A series of innovations relating to both design of film and the equipment for processing was a major factor addressing this limitation.

The purpose of a radiographic procedure is to provide *visibility* of the internal structures and conditions within the human body. However, visibility of specific objects within the body is determined by a combination of three major image characteristics: contrast, detail as limited by blurring, and visual noise as illustrated in Figure 3.

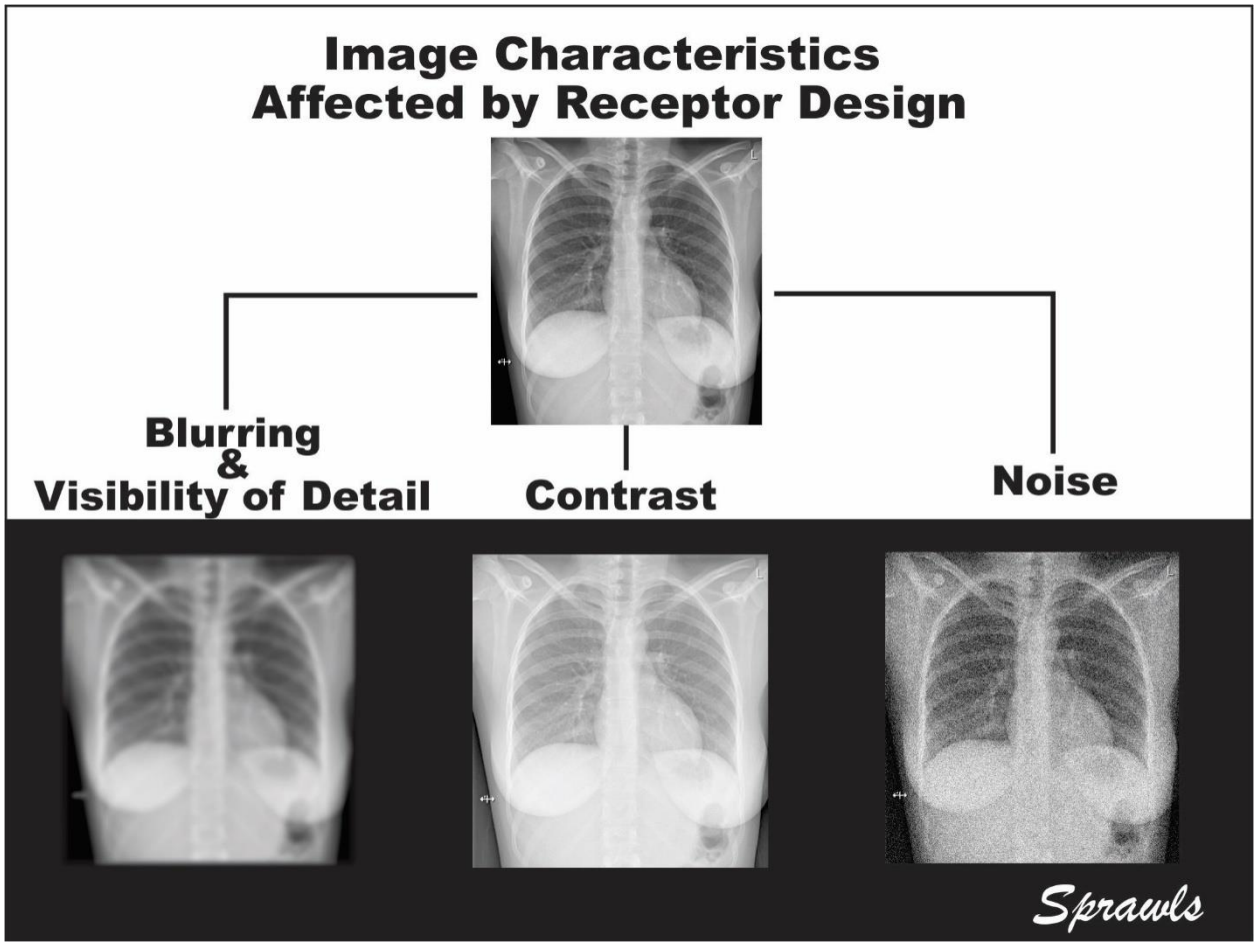

Figure 3 Three basic image quality characteristics that are affected by receptor characteristics and design.

Each of these specific characteristics has a direct effect on visibility of anatomical structures and conditions within the body. However, it becomes somewhat complex because of relations among the three characteristics and especially their relationship to the required x-ray exposure to form images. Each of these image characteristics and exposure requirements is determined by the design characteristics of a receptor. This has been the focus of research and development over many years.

The goal has been to produce images that provide the necessary visibility for specific clinical applications and with the lowest possible radiation exposure to the patient. While it is, and will always be, necessary to use certain quantities of radiation to achieve the required image quality for specific procedures there has been the continuing improvement in the *image quality-to- radiation exposure* relationship that has occurred with the many advances in receptor design.

The functions of a radiographic receptor are to first *absorb the x-radiation*, and then *convert* the x-ray image into some visible form. The major challenge throughout the continuing development of receptors has been to get the highest possible absorption in the thinnest possible layer of material within the receptor. Why is this so significant? First, high absorption decreases the quantum noise in relation to the required receptor and patient radiation exposure. Radiation that is not absorbed by the receptor does not contribute to image formation but does increase patient exposure. That is because it must be compensated for by increasing the exposure to the receptor and patient.

The absorption in the receptor is determined by a combination of three factors: thickness, characteristics of the material (density and atomic number, Z), and the x-ray spectrum. The research and development of receptors has focused on designs that provide a balance among these factors.

2. Glass Plates, the First Radiographic Receptor

At the time of Roentgen's introduction of radiography the practice of photography was well developed and photographs were produced with light-sensitive emulsions coated onto various materials including glass plates. Since these emulsions were also sensitive to x-radiation the coated glass plates became useful and available radiographic receptors. At that time the practice of photography was somewhat complex and required considerable materials, knowledge, and experience. It was the commercial photographers who had this capability and promoted radiography as a "new kind of photography" and opened studios for this purposed. Rather than going to a hospital or clinic for a radiograph a person could go to the local photographer. Photographers were already using large plates for portraits and these were appropriate for radiographs of anatomical regions including the chest.

While photographic emulsions are sensitive to and can form images from x-ray exposure, they are relatively thin and do not provide high absorption. This was one of the first major issues addressed in receptor development. The first was to design thicker emulsions specific for x-ray direct exposure and then the introduction of intensified radiography using fluorescent screens as described later.

Glass plates remained the base material for radiographs for many years, until the development of flexible and more convenient base materials when the receptor became known as a film rather than a plate. A radiograph on a glass plate is shown in Figure 4a and 4b(being developed).

Figure 4.a Radiographs recorded on a glass plates being chemically processed. They are rigid, fragile, and relatively heavy to handle
b. An early radiograph recorded on a glass plate.

Glass plates were used for radiography because they were the only practical materials available to support photographic emulsions at that time. Their extensive use in photography provided the experience and resources to support the early days

of radiography. However, they presented considerable challenges for use as radiographic receptors. These included being fragile, difficult to handle and store, expensive, and sometimes limited availability.

3. The Evolution of Film Base Materials

The considerable limitations of glass plates motivated the development of different base materials with the desirable characteristics of flexibility, transparency, and being relatively thin. It was the flexibility that was to make mechanical (often referred to as automatic) chemical development and processing of film possible to replace manual or hand processing. This was a major step in increasing productivity and improving image quality and consistency.

Cellulose Nitrate

In the 1910s glass plates were generally replaced with film bases composed of cellulose nitrate. This had many of the desirable properties but unfortunately was very flammable, resulting in some disastrous fires, especially in hospitals where large quantities of film were stored.

Cellulose triacetate-safe film

In the 1920s the nitrate flammable material was replaced with cellulose triacetate which was promoted as a safe, non-flammable, film.

Blue Tinted Film Base

In the 1930s it was discovered that adding a light blue tint to the film base provided improved viewing comfort with less eye strain than the completely clear and transparent film bases.

Reduced Base Light Crossover

This will be discussed later but with the films with emulsions coated on both sides and placed between two fluorescent intensifying screens an undesirable effect was light produced by the intensifying screen on one side passing through the film base and exposing the emulsion on the opposite side. Because the light could spread as it passed through the film base this added some blurring to the image. Over the years several approaches were developed to reduce light crossover. One was the development of film base materials that were less transparent to the light from intensifying screens but completely transparent to visible light for viewing images.

4. The Sensitive Photographic Emulsion

It is the relatively thin chemical emulsion coated onto the base that forms the image, commonly referred to as "the emulsion" because it consists of a suspension of many individual silver halide crystals within a supporting material. The recording and producing of an image, generally known as the "photographic process," by the silver halide crystals will be described later along with the chemical development that is a major phase of image formation.

Film Transparency and Optical Density

The emulsion coated onto the transparent base becomes opaque when it is exposed to radiation (either x-ray or light) and then chemically processed. The opaqueness can be quantified and expressed as *optical density*. The density value is inversely related to the amount of light that penetrates or passes through the film and is a logarithmic relationship. The exposure that forms an image can be over a large range of several decades (factors of 10) but the resulting density values are limited to a range of not more than 0 – 4 density units.

Densitometers are instruments for measuring the optical density at a specific point on a film by passing a small beam of light through it. They were used extensively for monitoring the variations in film density associated with the chemical processing in the context of quality control programs and for collecting data to plot graphs as described below.

Film Characteristic (H & D) Curves

The relationship of optical density to exposure determines the contrast characteristics of an image. Within a receptor it is the film that determines the contrast, the most predominant image quality characteristic. For a specific radiographic image the contrast is determined by a combination of three factors: the design of the film, the amount of exposure, and the conditions associated with the chemical processing. The performance of a film with respect to these three factors can best be expressed with a graph relating optical density to exposure as shown in Figure 5.

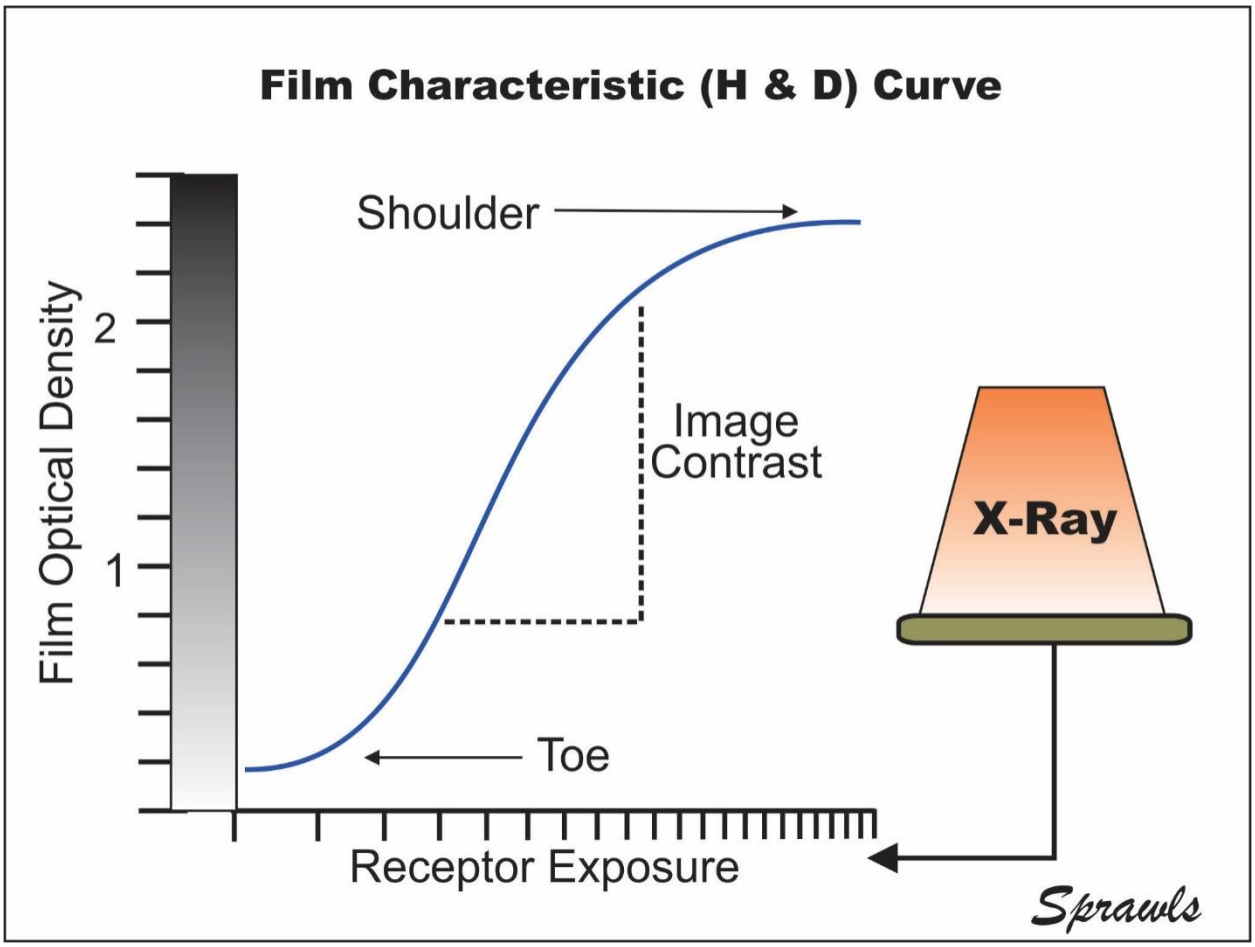

Figure 5. The characteristic (H & D) curve relating film 0ptical density to receptor exposure that is on a logarithmic scale.

This graphical method was developed for photographic film by Hurter and Driffield and carries their name, or initials H & D along with the name characteristic curve. The general contrast characteristics of a film represented by the curve are illustrated in Figure 5.

The usual method for producing a film characteristic curve is to expose a film to progressively increasing steps of exposure with an instrument known as a sensitometer, process the film, and then measure the density at each step with a densitometer.

The function of the film is to convert the image contrast coming from a patient's body into visible contrast and display it for viewing, typically on an illuminated view box. This conversion of exposure contrast into visible optical contrast is determined by the slope or gradient of the characteristic curve at each exposure value. For every film there are three distinct exposure ranges where the contrast formation is different. Maximum contrast is produced in the region representedby the steepest or greatest slope or gradient. This is a major characteristic of a film and determines which clinical procedure (chest, mammography, etc.) it is designed for. There are three mathematical factors that can be used to express this. The film *gamma* is the numerical quantity expressing slope or tangent at the steepest, or maximum contrast, point along the characteristic curve. It is expressed as the difference in density for a 10 to 1 exposure ratio. A specific film under specific processing conditions will have one gamma value. It is a carryover from photographic film but not easy to measure for x-ray film within radiology departments. Also, it expresses the contrast just at one point along the exposure scale, the point of maximum contrast. As shown, the slope and contrast varies over the exposure range and this has a significant effect on overall image contrast. The *average gradient* is one value expressing the "average" slope over the range with adequate slope to contribute to image formation. Values for the gamma and average gradient depend on the design of the film, from "contrast" to "latitude" type films, and with values generally in the range of 3 to 4.

The more practical unit, the *contrast factor*,is the density difference for a 2 to 1 exposure ratio. This is easily determined with conventional sensitometers and densitometers and is used in film processing quality control activities. The contrast factor can be determined for each point along the exposure scale.

The Toe and the Shoulder

As shown in Figure 5 there are two regions, corresponding to low and high exposures where the slope and contrast decreases and becomes zero. This is because of the chemical nature within the photographic process. At low exposure values, relating to the toe of the curve, there is not sufficient exposure to initiate the formation of any useful density.

Base Density and Fog

The optical density represented by the toe of the curve comes from several sources. The film base is almost, but not completely, transparent. There is some density of the base material which is generally below 0.15 density units. Fog is the term for density that is within the emulsion that is not associated with planned exposure during an imaging procedure. There are several possible sources. These include exposure from environmental radiation, ageing of undeveloped film, especially at high temperatures, and over development. Measurement of the base + fog density is one important action in a quality control program. It should generally be below 0.2 density units.

Maximum Density (D max)

At high exposure values there is a limit to the formation of additional density and this is represented by the shoulder of the characteristic curve. This occurs because all of the available silver halide crystals within the emulsion have been activated and converted to dark metallic silver. Over the years film has been designed to produce higher maximum density. This extends the range of exposure that can produce useful image contrast (latitude) but might require special viewing conditions with brighter illumination. This has been especially valuable in mammography.

Film Latitude

The latitude of a film is the range of exposure that will produce useful and visible density values, generally specified as from 0.4 to 2.75 density units as illustrated in Figure 6.

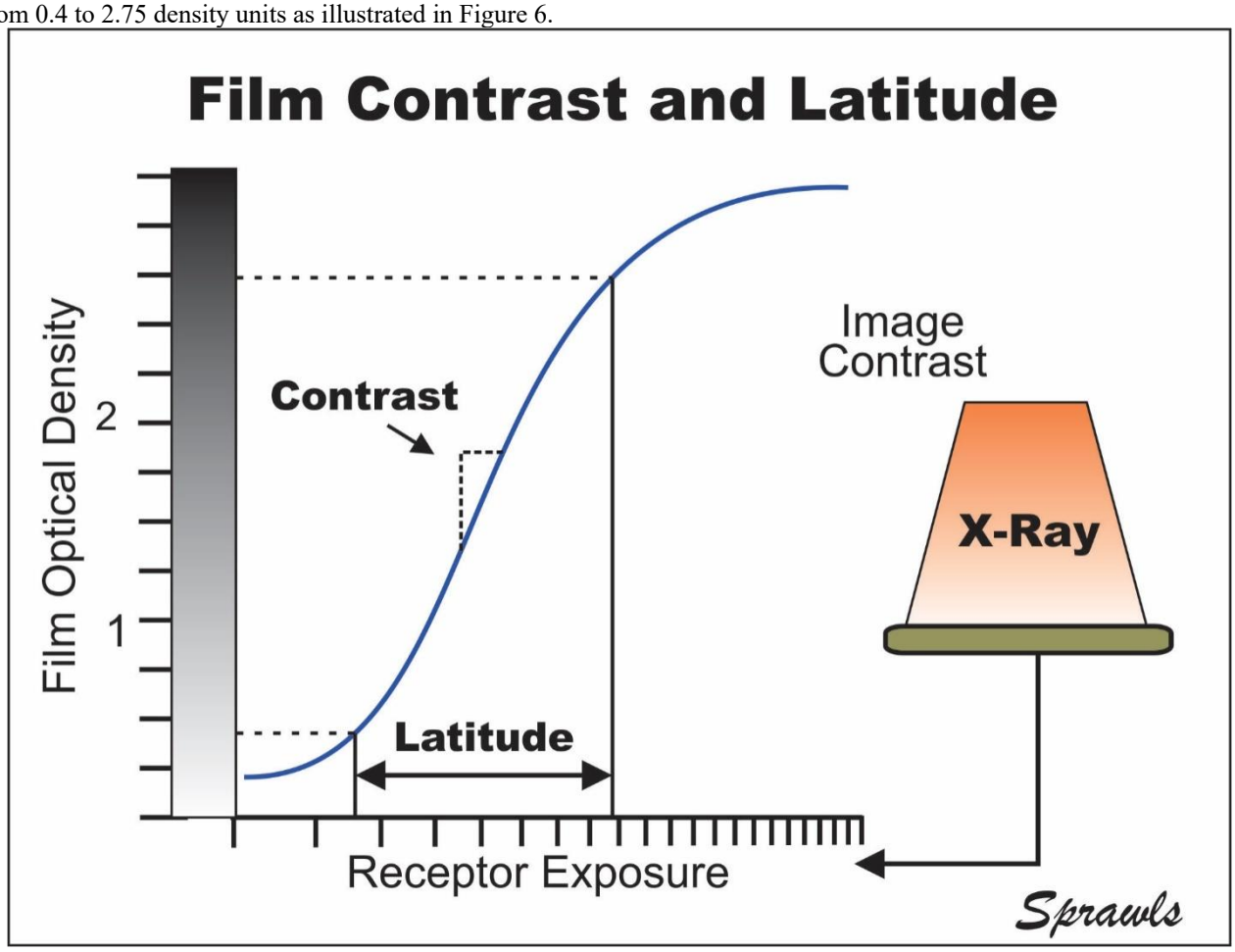

Figure 6. The latitude of film and its relation to contrast.

The latitude of a specific film is determined primarily by the emulsion design and chemical composition. It has always been one of the limiting factors of film for radiography. Film latitude is the general equivalent of dynamic range for digital

imaging systems. It is the range of exposure values to a receptor that can produce useful image contrast. Exposure outside the latitude range, either below in the toe or above in the shoulder, results in reduced or no contrast.

There are two major factors that can result in exposures outside of the latitude range and the loss of contrast. One is a mismatch of the exposure delivered to the receptor with what is actually required. This is generally referred to as an "exposure error" coming from two conditions. The most common was the selection of the technique factors, especially the quantities KV and MAS (in the units of kV and mAs) for a specific procedure. Automatic exposure control (AEC), also known as photo timing, contributed to reduced errors but was not always a solution. Others, and often less obvious, were variations in the exposure required by a receptor (its sensitivity or speed) caused by differences among receptor components and especially changing conditions in the chemical processing of film described later. All of these potential sources of exposure error were addressed in quality programs conducted by or under the direction of medical physicists.

The second factor contributing to reduced contrast in some areas of an image is the wide range of exposure coming from the patient's body because of variations in body thickness or density. The chest is an example. When the range of exposure extends beyond the latitude range contrast will be reduced. This was addressed by designing film with several different contrast-to-latitude relationships to fit specific clinical requirements.

5. Radiographic Film for Specific Clinical Applications

Throughout the history of radiography one of the constant challenges has been providing the correct exposure to a film to produce the appropriate image contrast. Contributing to this challenge has been both that of adjusting the exposure for each imaging procedure and also factors associated with the design and processing of the film that will be considered here. This relates to the contrast characteristics of film as illustrated in Figures 5 & 6. There is a limit to the range of exposure to a film receptor that will produce the desired contrast. Generally this must be within the film latitude, and also the characteristic curve gradient must be sufficient to produce the required contrast. These conflicting requirements have been addressed with advances in film technology and design of film with optimized characteristics for specific clinical applications, usually related to the anatomical regions being imaged. The specific challenge has been developing film that can produce the necessary high contrast and also have adequate latitude to respond to the range of exposure projected from the patient's body. There has been a variety of designs over the years but the three major types are illustrated in Figure 7.

General Radiography with Contrast Type Film

Film with similar contrast characteristics (H & D curve slope) were used for imaging most parts of the human body, including the skeletal system and the abdomen, This was generally referred to as "contrast" type film both to emphasize its ability to produce good image contrast and also to distinguish it from "latitude" type film used in other anatomical areas.

Chest Radiography with Latitude Film

The chest or thoracic area of the body is a special challenge in radiography because of the wide range of densities within. The lungs contain air and are large areas of low density very different from the much denser mediastinum containing the spine and heart. The problem is that this produces a wide range of exposure coming from the body and if this is greater than the film latitude there will be a reduction or loss of image contrast in some areas. Film designed to have relatively wide latitude was used for chest imaging.

Mammography Film

Effective imaging of the breast, especially to detect early-stage cancers, requires receptors with special high-quality characteristics compared to other radiographic procedures. These will be described in more detail later but here attention is given to the film, specifically the more advanced film design used for mammography. The breast is composed of soft tissue with generally similar physical density values that is the source of contrast for an image. The mammography process is developed with several features to produce high contrast. One is special x-ray spectra and the other is the design of the film described here.

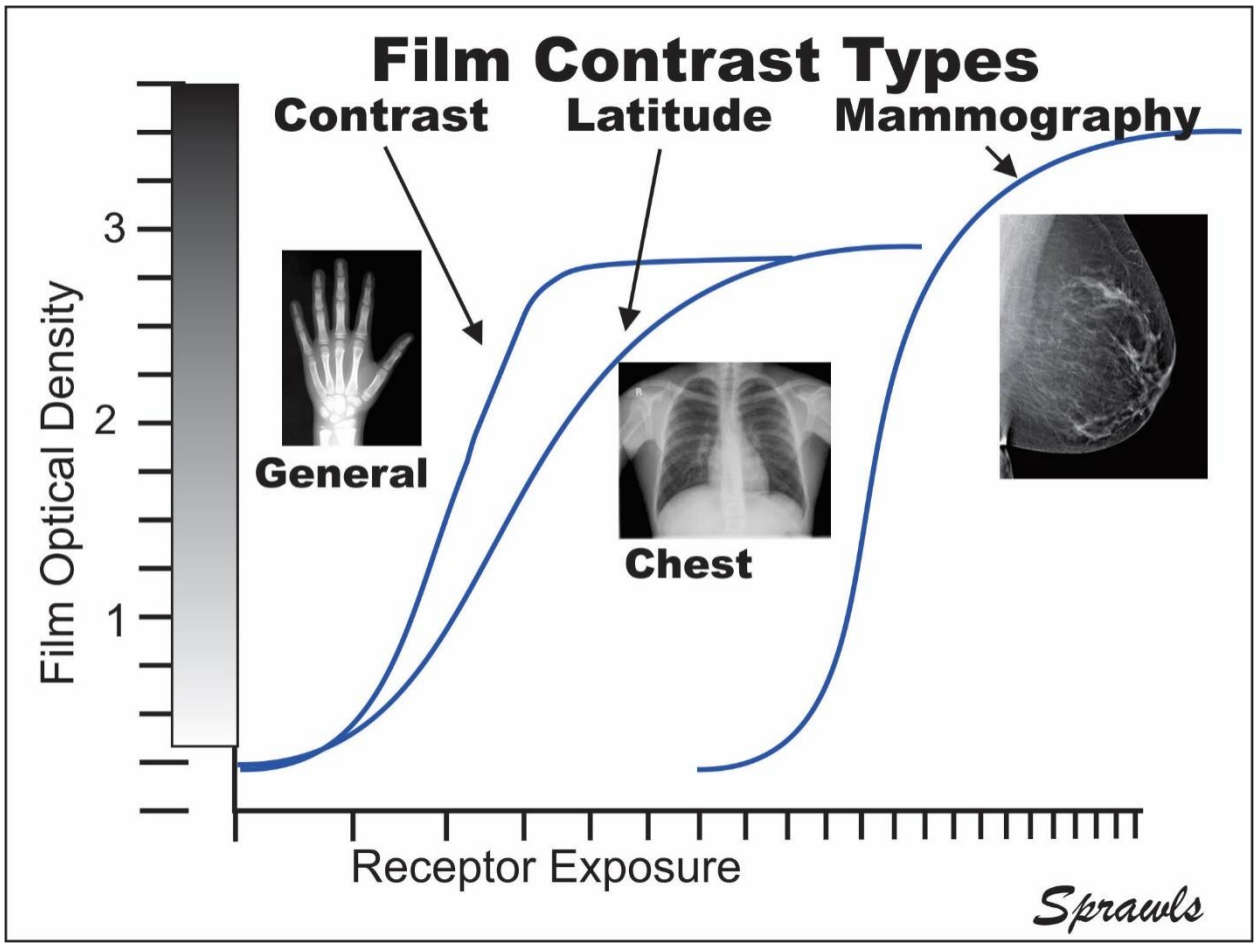

Figure 7. Different contrast characteristics of radiographic film for specific imaging procedures.

The requirements are for film with high contrast and wide latitude, the generally conflicting design characteristics. This is achieved in mammography film by having a high-contrast design (steep H & D curve slope) and extending the range into higher optical density or darkness values compared to other radiographic films as illustrated in Figure 7. This required that mammograms recorded on this type of film be viewed on special illuminators, or view boxes, that were brighter than those for other radiographic films.

Film Size and Shape

Four standard sizes and shapes for film-screen receptors (cassettes, screens, film) are:

8" x 10" (18cm x 24cm)
10" x 12" (24cm x 30cm)
11" x 14" (30cm x 35cm)
14" x 17" (35cm x 43cm)

The selection of which to use for a specific procedure was determined by the anatomical area to be images.

6. Radiographic Image Viewing

Images on transparent film were viewed by placing a source of light behind them. This was generally a flat illuminated surface, an illuminator, or more commonly known as a "view box" as illustrated in Figure 8.

Figure 8. Radiologist, Dr. Britton Gay, at Emory University viewing a radiograph in front of a view box.

Viewing Luminance (Brightness)

The performance of the human visual system is heavily dependent on the brightness of the image or objects being viewed.This limits the ability to visualize both small objects (detail) and objects with low contrast. Image viewing is the last but very important step in the total imaging process. Measuring the brightness of view boxes and taking corrective actions was an important of a quality control program. For general radiography a view box luminance of 1,500 cd/mm^2 was typical. Usually there was a small light, known as the "hot light" that would be used to view through dense areas in a film. Some film designed specifically for mammography had a higher maximum density and the images were much more dense or dark the conventional radiographs. This requires a brighter view box of approximately 3,000 cd/mm^2 or higher.

7. Chemical Processing of Film

Perhaps the most demanding aspect of film-based radiography was the chemical processing required to produce the images. It required time and effort by the staff, was a significant expense, and had significant and often undesirable effects on both image quality and potential patient x-ray exposure to patients. Because the chemical process is subject to considerable variability, good practice required quality control programs to maintain image quality and reduce the potential of unnecessary radiation exposure.

The formation of a visible image on film is a two-step process. The first is exposing the film with some form of radiation that produces the so-called "latent" or invisible image. The second step is the chemical processing that converts the invisible latent image into a visible image on the film. This is generally known as the "photographic process."

The Photographic Process

Film density is produced by converting silver ions into metallic silver causing each processed grain to become black. The process is illustrated by the sequence of events shown in Figure 9.

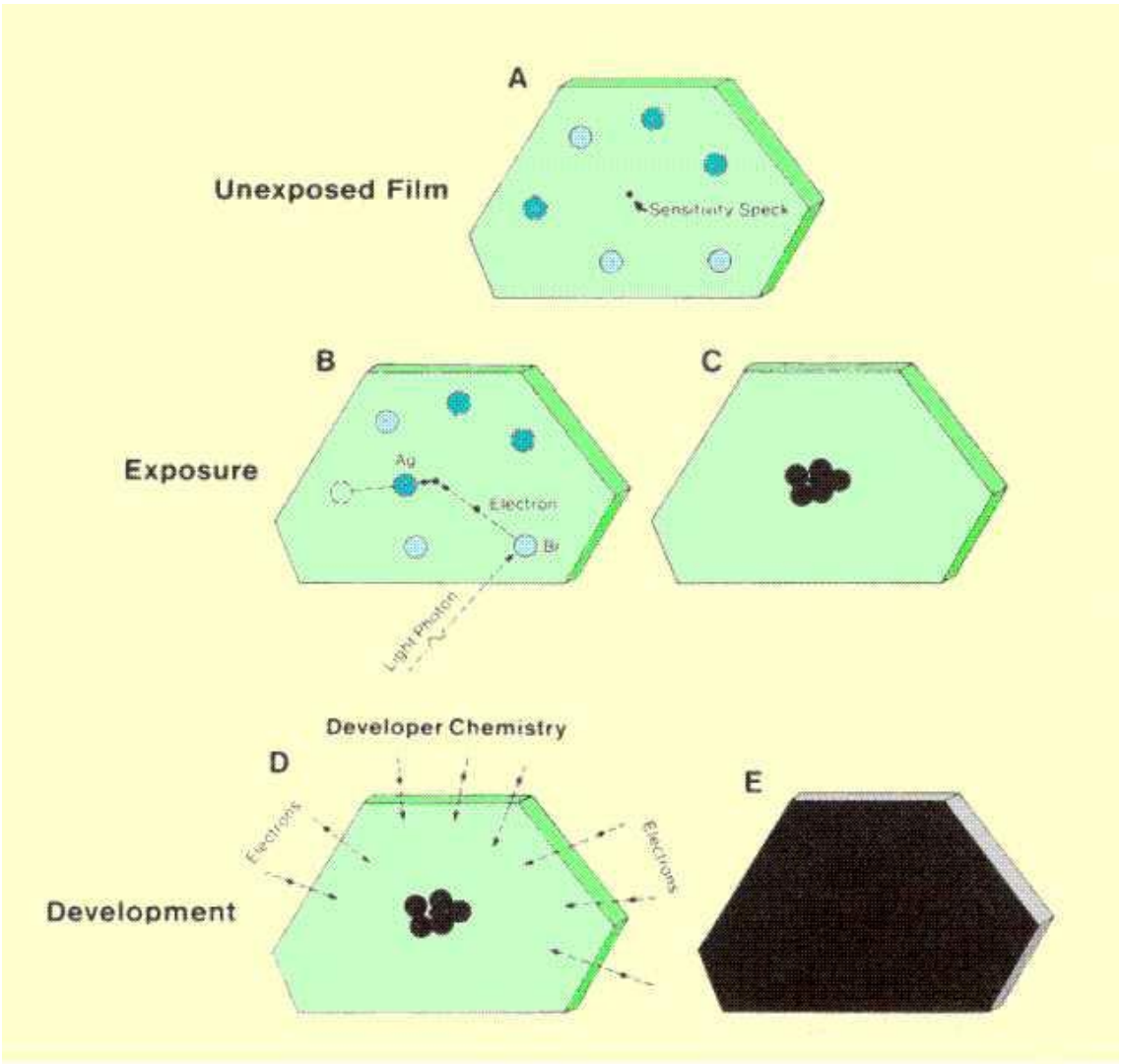

Figure 9. Sequence of events that convert silver halide grains into black metallic silver

Each film grain contains a large number of both silver and bromide ions. It was probably Louise Daguerre in France who first established this process around in 1839. The silver ions have a one-electron deficit, which gives them a positive charge. On the other hand, the bromide ions have a negative charge because they contain an extra electron. Each grain has a structural "defect" known as a sensitive speck. A film grain in this condition is relatively transparent.

The Processing Cycle

The chemical processing of an exposed film to convert the invisible latent image into a visible image consists of four steps as illustrated in Figure 10

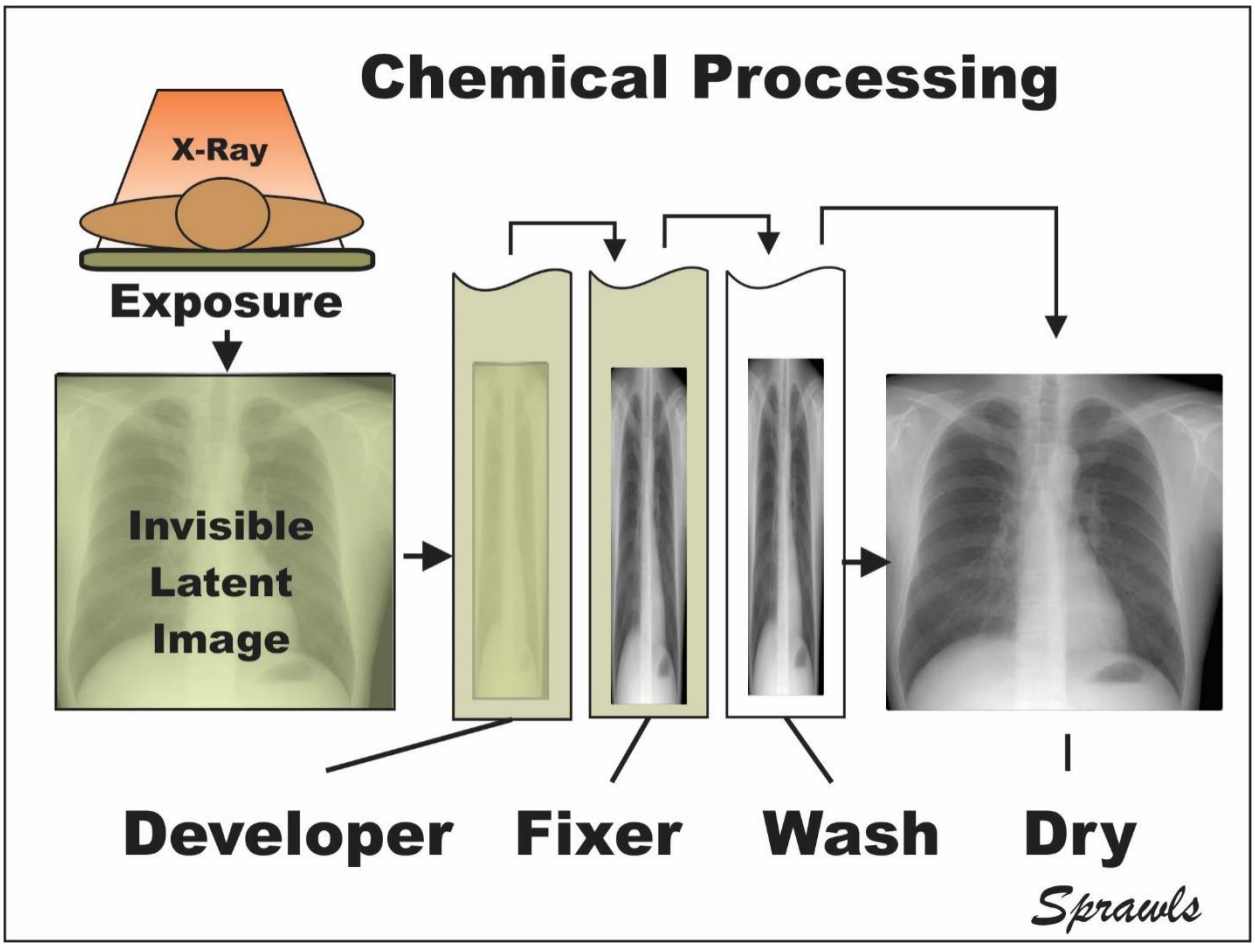

Figure 10. The series of steps in the chemical processing of radiographic film.

Developer

The invisible latent image is converted into a visible image by the chemical process of development. The developer solution supplies electrons that migrate into the sensitized grains and convert the other silver ions into black metallic silver. This causes the grains to become visible black specks in the emulsion.

Fixer

After leaving the developer the film is transported into a second tank, which contains the fixer solution. The fixer is a mixture of several chemicals that perform the following functions.

Neutralizer

When a film is removed from the developer solution, the development continues because of the solution soaked up by the emulsion. It is necessary to stop this action to prevent overdevelopment and fogging of the film. Acetic acid is in the fixer solution for this purpose.

Clearing

The fixer solution also clears the undeveloped silver halide grains from the film. Ammonium or sodium thiosulfate is used for this purpose. The unexposed grains leave the film and dissolve in the fixer solution. The silver that accumulates in the fixer during the clearing activity can be recovered; the usual method is to electroplate it onto a metallic surface within the silver recovery unit.

Preservative

Sodium sulfite is used in the fixer as a preservative.

Hardener

Aluminum chloride is typically used as a hardener. Its primary function is to shrink and harden the emulsion.

Wash

Film is next passed through a water bath to wash the fixer solution out of the emulsion. It is especially important to remove the thiosulfate. If thiosulfate (hypo) is retained in the emulsion, it will eventually react with the silver nitrate and air to form silver sulfate, a yellowish brown stain.

Dry

The final step in processing is to dry the film by passing it through a chamber in which hot air is circulating.

Controlling the Development Process

The chemical processing of film to produce a visible image is a complex process consisting of several functions as described above. The first phase, development, is especially critical because it is subject to significant variation that can affect the quality of an image and indirectly x-ray exposure to patients.

As a film is placed in the developer solution the process of producing a visible image begins. It is a continuing process for about 25 seconds in the more recent systems where the transport speed is well regulated. The rate of the development action is determined by a combination of factors that can be the source of instability and variability leading to development errors, either under- or over-development. The desired level of development is when all of the exposed silver halide grains are converted to black silver contributing to visible film density.

The level, or completeness, of development is determined by the combination of time in the developer solution and the rate of the developing action. When mechanical or automatic processors became available the time was well regulated and became less of a variable, especially when compared to manual/hand processing. The rate of development is determined by design composition of the chemistry and how it matches specific emulsion characteristics, to what level has the chemistry been depleted and replenished, and the temperature of the developer solution. In automatic processors the temperature is controlled by a thermostat but that could be set at the appropriate temperature. Processing test films exposed with a sensitometer and the resulting densities measured with a densitometer is a standard quality control procedure for monitoring the level of processing.

If a film is under-developed some of the exposed grains do not result in visible density with two undesirable effects, reduced contrast and reduced sensitivity (speed). The significance of the reduced sensitivity is that it might be compensated for by increasing the x-ray exposure to the patient.

If a film is over-developed some of the silver halide grains that were not exposed will be converted into visible density with two undesirable effects. One is the reduction in image contrast and the other is an increase of density in the regions of low exposure that is known as fog. The characteristic curve shown in Figure 11 shows the effects of variations in the level of development.

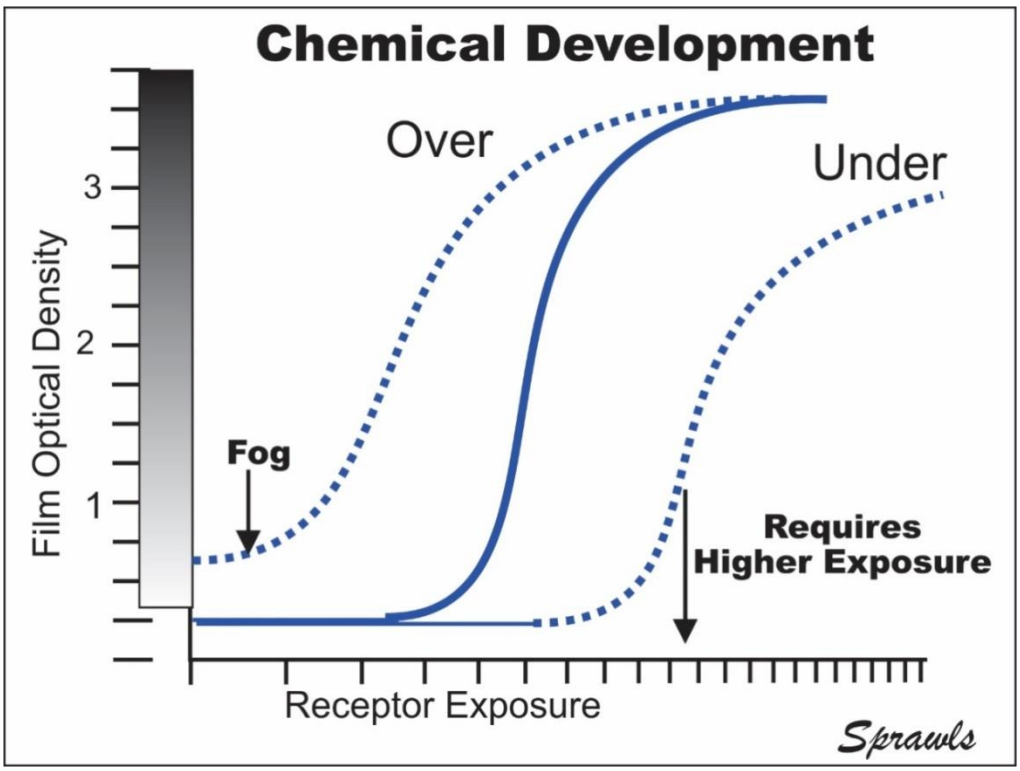

Figure 11. The effects of incorrect levels of development on film characteristics.

The chemical processing of film, especially the development phase, was generally the most unstable and variable part of the radiographic imaging process. In the early days when film was processed by manually placing it in and removing from the developer solution the time was a variable. With machine (often called automatic) processing the time was generally well regulated so the variation was in the *rate of development.* This was determined by the combination of two conditions, the composition of the developer chemistry and the temperature.

Full development of film required chemistry that was formulated to match specific film emulsions (not always achieved) and replenished as the developer chemistry was consumed in the ongoing process. In processors the developer was automatically replenished by pumping a small amount of new chemistry in as each film passed through.

Because the chemical processing of film was a major factor in both image quality and x-ray exposure requirements it was a very important quality control activity usually conducted by or under the direction of medical physicists. The usual procedure was to expose a test film with a sensitometer, process it, and then measure the resulting densities with a densitometer. The values were compared to reference values and also charted over time to monitor consistency.

8. Intensified Radiography

Even though the silver halide crystal emulsion can be exposed by x-radiation and form an image the sensitivity is very low in comparison to exposing with light. This is because the thin emulsion in not a good x-ray absorber and also the way in which the silver halide crystals require exposure by several individual photons. The energy of one x-ray photon is equivalent to many light photons. Therefore, for the same amount of energy delivered to a silver halide film the effect and image formation will be much greater if the exposure is with light rather than by x-radiation.

Although a few radiographic procedures continued to use direct film exposure, such as dental and industrial, intensified radiography became the common method.

The process of intensified radiography is illustrated in Figure 12.

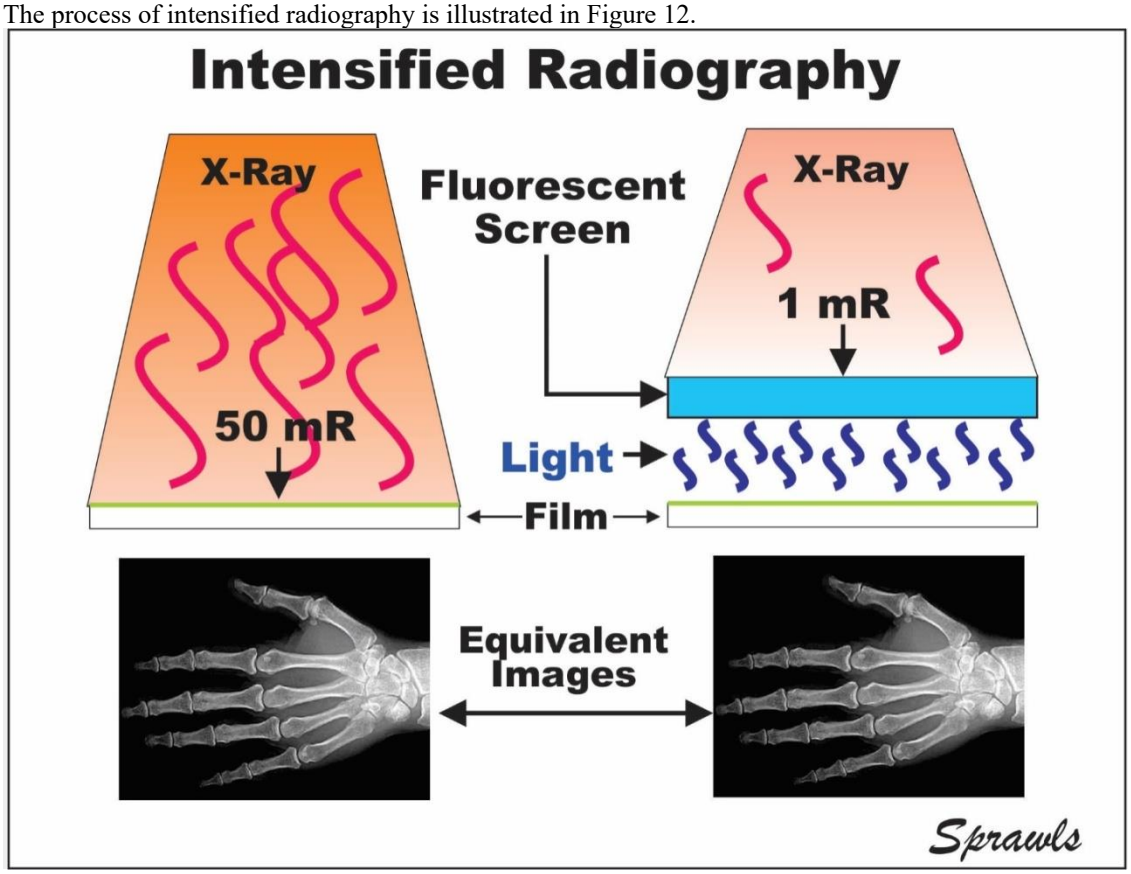

Figure 12. Using a fluorescent screen to increase, or intensify, the exposure to film from x-radiation.

An intensifying screen is a sheet of fluorescent material, or phosphor, placed in contact with the film. The size and shapes of intensifying screens matched that of the films and cassettes described earlier.The light produced within the screen from x-ray exposure is much more effective in exposing the film and producing an image compared to direct x-ray exposure.

Intensification Factor

The contribution of an intensifying screen to film exposure can be expressed as the *intensification factor* which is the ratio of x-ray to light exposure required to produce the same photographic effect or image. While these values were not generally useful for adjusting actual exposures in clinical practice they do demonstrate the great advantage in using intensifying screens. Values depend on the design characteristics of the screens such as thickness and composition as described later. A value of 50 is used in Figure 12 as an example. While this illustrates the great value in using intensifying screens to reduce exposure to patients it does not provide adequate information on the actual exposure required by radiographic receptors to produce an image.

Receptor Sensitivity and Speed

A major characteristic of every radiographic receptor is the x-ray exposure it requires to produce an image. This is expressed as either a *sensitivity* or *speed* value. Values depend on design characteristics of both the film and the intensifying screens and extend over a relatively wide range as shown in Figure 13.

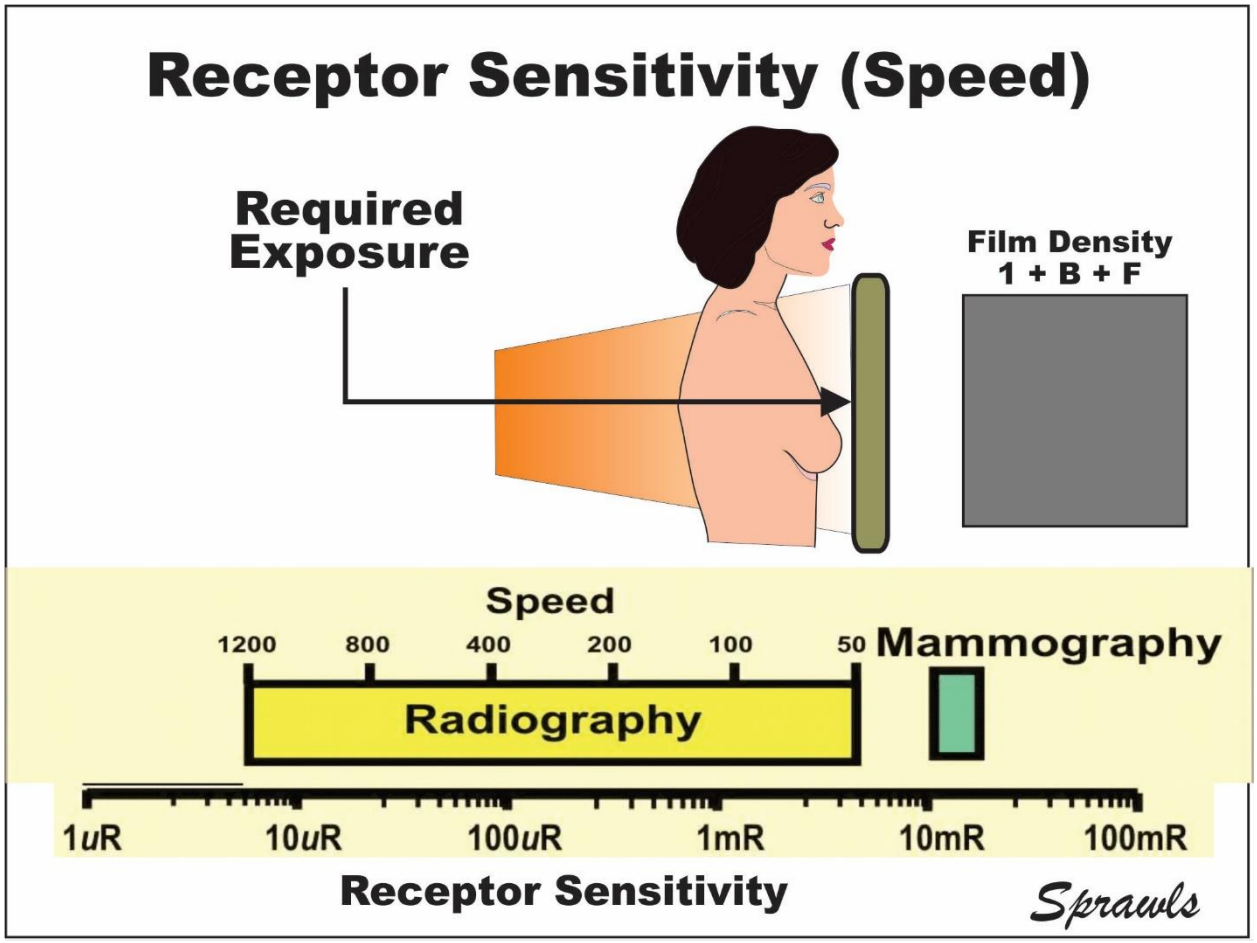

Figure 13. Range of exposure values required by receptors to form an image.

The standard procedure is to express the exposure requirement of a receptor as the exposure that produces a film optical density of one density unit above the base + fog density (1+B+F). Base plus fog density corresponds to the toe of the characteristic curve shown in Figure 5. A density value of one unit above the base-plus-fog is relatively close to the middle of densities visible in a typical radiograph and provides a reasonable reference for comparing procedures with respect to exposure to patients.

The *sensitivity value* is the actual exposure required to form the reference density value, 1+B+F, on a film. It can be measured and is useful for comparingexposure requirements of general radiography with other methods including mammography and fluoroscopy.

Receptor *speed* is a concept carried over from photography where it is used to express the exposure requirements of film. Increased speed implies that a film or receptor is responding faster and therefore requires less total exposure.

For radiographic receptors speed is not a precisely defined or measurable quantity but is more of a relative quantity for comparing receptors. At some time a specific screen-film receptor was designated as "par speed" and assigned a speed value of 100. Other receptors are compared to this to determine speed values. A general relation of speed and sensitivity values is given by:

Sensitivity (mR) = 128/speed.

Intensifying Screen Blurring and Visibility of Detail

The advantage of using intensifying screens is the great reduction in x-ray exposure required to produce an image compared to exposing film directly. As indicated in Figure 13 receptors using intensifying screens were available over a wide range of sensitivity or speed values. The question is why not always use the more sensitive receptors to reduce exposure to patients? The reason is that intensifying screens add blur to the image that results in reduced visibility of detail.

The amount of blurring is generally determined by the thickness of a screen which also affects its sensitivity. This is because thinner screens absorb less of the radiation and require more exposure to produce an image. The major factor in selecting the appropriate intensifying screen for a specific clinical procedure is this inverse relation between sensitivity and image quality. The general effect of screen thickness on both exposure requirements and image detail is illustrated in Figure 14.

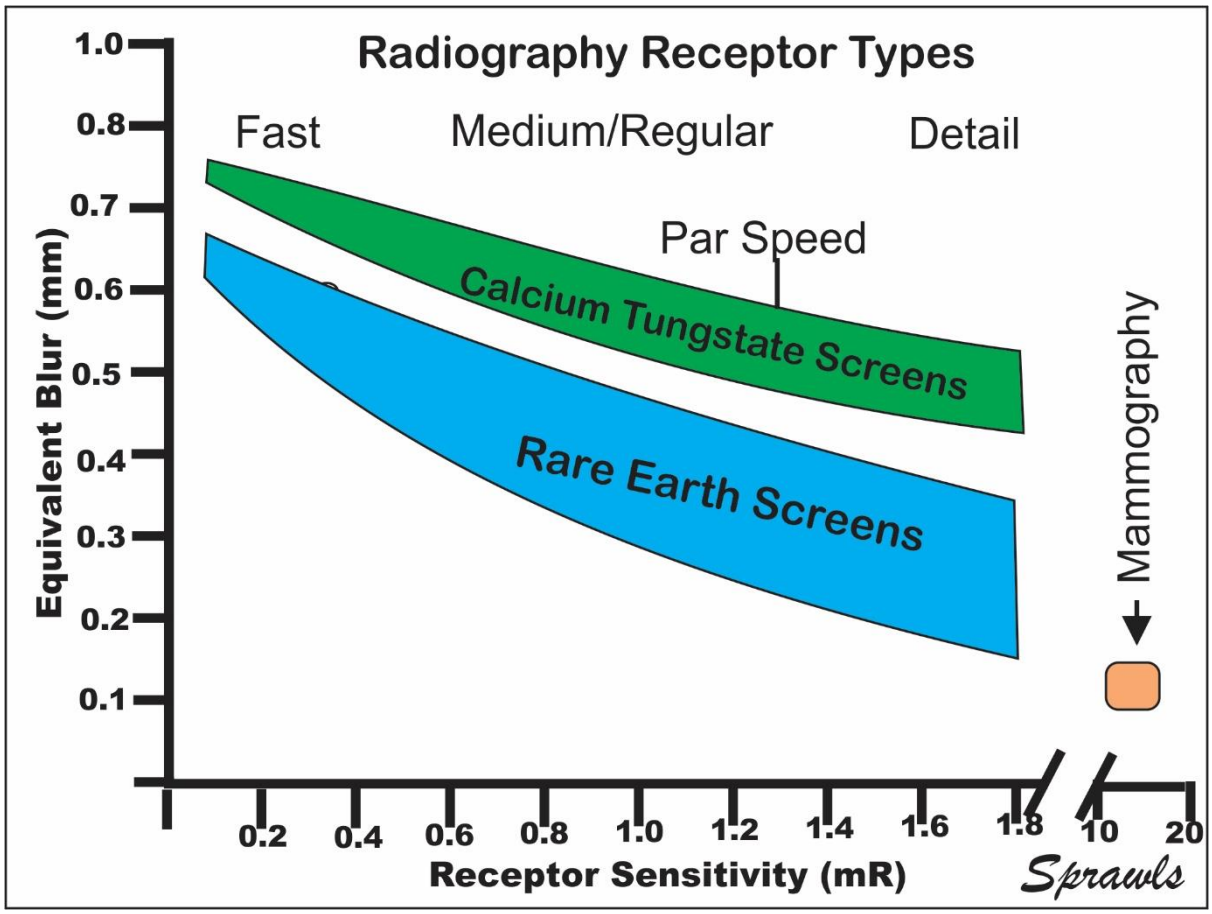

Figure 14. The general relationship between image detail and exposure requirements for the film-screen receptors available to an imaging facility. Also shown is the advantage of the transition from calcium tungstate to rare-earth intensifying screens.

Most intensifying screen manufacturers had commercial or trade names for their various screens. Most followed a general generic classification into three major types with names emphasizing the advantage, either high image quality or reduced exposure to patients. The three types were detail, par, and high speed. Figure 14 shows a general comparison and how each type relates to the thickness of the screen.

Light produced by the x-radiation occurs throughout the thickness of the screen. Light produced away from the side of the screen in contact with the film spreads before reaching the film. It is this spreading of light within the thickness of a screen that produces the blurring. In general, the amount of blurring increases with screen thickness. Thinner "detail" screens produce less blurring and better image detail but absorb a relatively small fraction of the x-radiation. Therefore, a higher exposure must be used to produce an image compared to the thicker "high speed" screens.

The blur produced within an intensifying screen generally has a Gaussian profile, or point spread function, as illustrated. For the purpose of radiographic system analysis and comparing screen blur to focal spot blurring it is appropriate to use *equivalent blur* values. This is the dimension of a blur with a uniform intensity distribution that has the same effect on visibility as the actual Gaussian distribution. For film-screen receptors equivalent blur values are calculated from modulation transfer function (MTF) curves generally provided by the manufacturers. Values are obtained for x-ray tube focal spots when measurements are made with a star test pattern. In a digitized image pixel size corresponds to an equivalent blur value. Table 1, discussed later, compares the equivalent blur values, speed numbers, and exposure sensitivity for receptors provided by one manufacturer, Kodak, in the 1990s.

A continuing design and development goal for intensifying screens has been to increase x-ray absorption to reduce exposure required while minimizing screen thickness to reduce blurring…the two conflicting requirements.

A common method for achieving this is the use of dual-screen receptors and film with sensitive emulsion on both sides as illustrated in Figure 15.

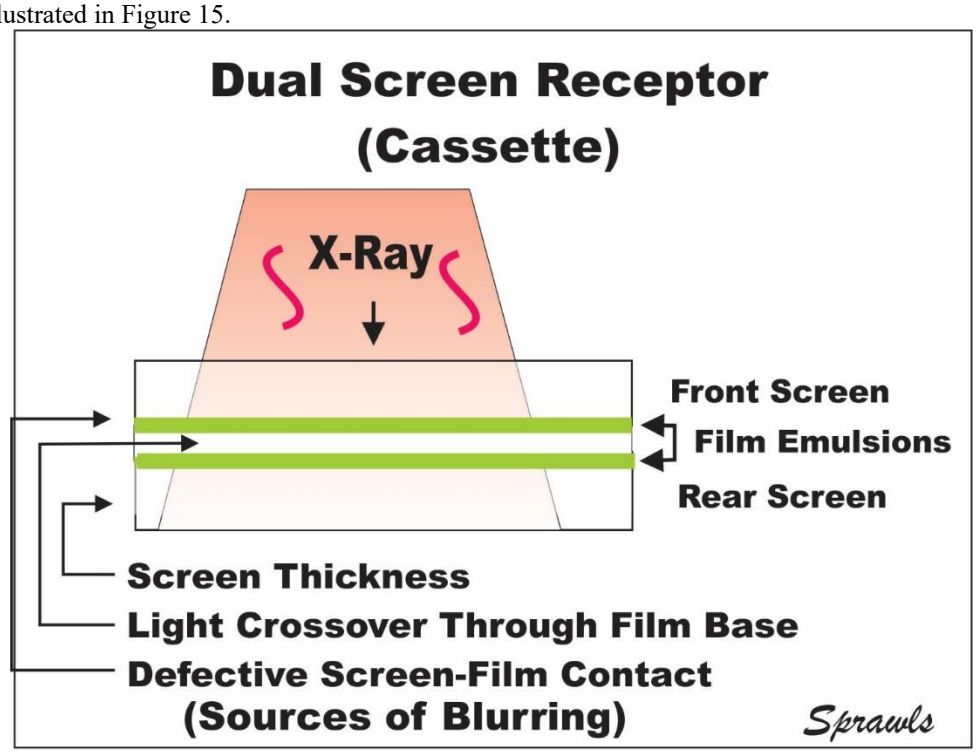

Figure 15. The typical radiographic receptor consisting of film with sensitive emulsion on both sides placed between two intensifying screens.

The advantage of this design is it provides the x-ray absorption of the two screen thicknesses combined but the blurring is related to just one screen thickness.

Dual screen receptors were used for most radiographic procedures with the exception of mammography where one thin screen and single-emulsion film is used to produce images with high detail—a requirement in mammography for the visualization of very small calcifications, one of the signs of cancer.

The dual-screen receptor does provide a significant advantage with respect to the "detail to dose" relationship but it introduces an additional, generally small, source of blurring. That is the possibility of some of the light produced by one of the screens passing through the film base and exposing the emulsion on the other side. Over the years several developments have addressed this problem. One has been to have base materials that are less transparent to the wavelength (color) of light produced by the screens. Another was the development of tabular, or flat, silver halide crystals that decreased light passing through the emulsion and into the film base.

A third potential source of blurring is defective contact between the film and screen surfaces. If there is some space, even very small, light can spread and produce blurring. This is an abnormal condition that might occur within defective cassettes and tested for in the context of quality control programs.

9. Radiography Image Noise

Visual noise, sometimes referred to as mottle, is an undesirable characteristic that reduces visibility of some anatomical and pathologic features, especially those with low contrast that often includes small objects. In radiography there are two specific and different sources of noise--structural and quantum.

Structural Noise

Structural noise is produced by the granular, or grainy, elements within the screens and film. Intensifying screens are in the form of many small crystals. Film is an emulsion containing individual silver halide crystals. If these individual elements are visible in an image it appears as a form of noise. In photography it's the individual silver halide grains that are the potential source of noise that is most commonly referred to as "grainy" photographs. Developments have produced both screens and films with less structural noise and in modern radiography it is not the predominant source of noise.

Quantum Noise

In radiography, along with other x-ray imaging methods, the predominant source of image noise is from the random distribution of the x-ray photons actually absorbed in the receptor, quantum noise. Since the amount of quantum noise is inversely related to receptor (and patient) exposure it is a major factor in managing radiation dose to patients. An appropriate procedure technique is when the quantum noise level has been set to produce just the necessary image quality for a specific clinical procedure, and not any lower. Reducing the noise beyond that results in unnecessary exposure to the patient.

In film-screen radiography the quantum noise level is determined by the characteristics of the receptor that has been selected for a specific procedure. The major factor determining the noise is the concentration of photons (exposure) actually absorbed in the receptor. This is the lowest photon concentration anywhere along the imaging process and is known as the "quantum sink" as illustrated in Figure 16.

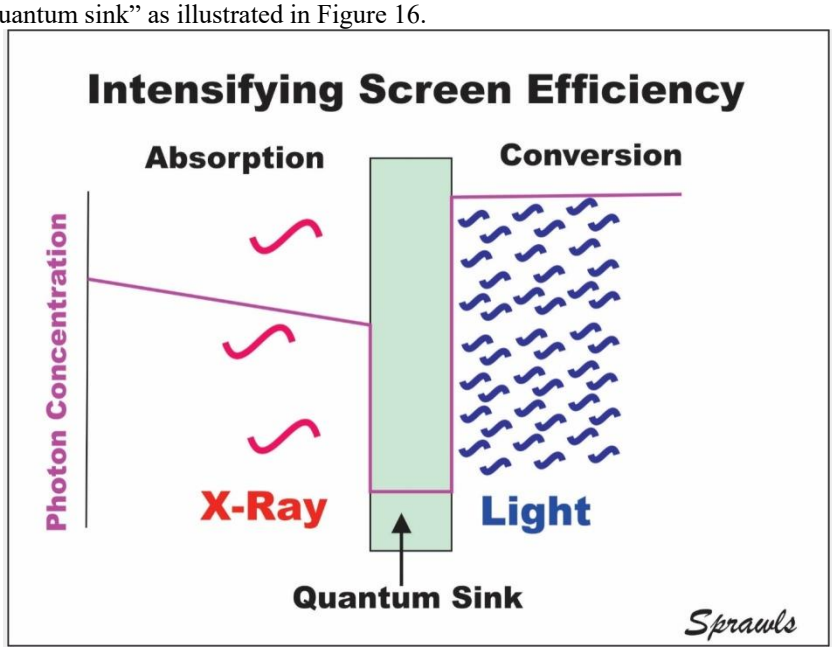

Figure 16. The two efficiencies of an intensifying screen and the quantum sink.

There are efficiency values associated with each of the two major functions of an intensifying screen; *absorption* of the x-radiation and *conversion* to light. Both are determined by the design (thickness and composition) of the screens. An increase in both efficiencies provides the advantage of increasing receptor sensitivity (speed) and reducing exposure to patients but can have an adverse effect on image quality.

The best image quality with the lowest patient exposure is obtained with quantum sink at the highest possible value representing the highest concentration of absorbed photons.

Conversion Efficiency and Film Sensitivity

A combination of two factors can reduce the quantum sink to a lower value for a specific receptor input exposure and increase the quantum noise. One is the screen x-ray-to-light conversion efficiency. Increasing this would make it possible to expose film and form an image with less x-radiation but the lower concentration of absorbed photons would increase quantum noise. In the development of intensifying screens the effort is not to get the highest possible conversion efficiency but a value that provides a balance between patient exposure and image quality, specifically quantum noise.

The sensitivity or speed of the film also affects the quantum sink. Using a more sensitive or higher speed film that requires less light reduces the quantum sink value and increases quantum noise.

While it was possible to develop radiographic receptors that require less x-ray exposure using either screens with higher conversion efficiencies or film with greater sensitivity these would not be useful because of the high noise.

Absorption Efficiency

The first function of an intensifying screen is to absorb the x-radiation. A design goal is to absorb a large fraction of the radiation because what is not absorbed is "wasted" and contributes to increased patient exposure but not to image formation. The fraction absorbed is determined by three major factors. One is the screen thickness described earlier that contributes to image blurring. The other two factors are the chemical composition of the screen and the x-ray spectrum which must be considered together.

10. Intensifying Screen Composition

The chemical composition and physical structure of intensifying screens have developed over the years with the continuing goal of improving image quality with reduced x-ray exposure. This has been divided into two very distinct eras based on the phosphor or fluorescent materials used in the screens, calcium tungstate and the rare earth elements.

Calcium Tungstate

Soon after Roentgen's discovery and development of the radiographic process calcium tungstate was found to be an effective fluorescent material for converting x-radiation into light and used as intensifying screens. The very productive inventor, Thomas Edison, and his staff were investigating many substances with fluorescent properties in their efforts to develop light sources. This experience contributed to the selection of calcium tungstate for use as an x-ray converter. Calcium tungstate, CaWO4, is a compound with several desirable properties. It is fluorescent when exposed to x-radiation, can be formed into thin sheets of relatively consistent and stable composition, and tungsten with a relatively high atomic number (Z=74) is an effective x-rayabsorber. While the introduction of calcium tungstate intensifying screens was a major contribution to radiography because of the reduction in x-ray exposure required to form images there were continuing issues with image quality.

Carl V. S. Patterson continued the development of screens with significant improvements. In 1916 he introduced screens composed of synthetic calcium tungstate that had several advantages over the natural form. *The Patterson Screen Company* also developed and produced fluoroscopic screens including the handheld fluoroscope that was popular during the early days of x-ray imaging. In 1943 *Du Pont* Company acquired the *Patterson Screen Company*.

Even with improvements in composition and the physical characteristics of calcium tungstate intensifying screens a continuing limitation was absorption efficiency. With the necessity of keeping screen thickness relatively low to control blurring the absorption of x-radiation was also relatively low. A contributing factor was this: with an atomic number of 74 tungsten has an absorption K edge at 69.4 keV. The significance is that much of the x-ray spectrum, especially when using medium and low KV values, is below the K-edge energy where absorption is diminished. It was this characteristic that provided an interest in developing other fluorescent materials.

Rare Earth Elements and Intensifying Screens

A major innovation in screen-film receptor technology beginning in the 1970s was the conversion from calcium tungstate to fluorescent materials composed of some of the rare earth elements. These included:

• yttrium oxysulfide
• lanthanum oxybromide
• lanthanum oxysulfide
• gadolinium oxysulfide.

Rare Earth Elements

The "rare earths" are a group of 17 chemical elements that have a variety of magnetic, luminescent, and electrical properties that contribute to their value in many modern technology applications. At least two, lanthanum and gadolinium,had properties making them effective elements for intensifying screens. They are not used alone but in compounds with additional elements as activators. The compounds had the desirable fluorescent yields contributing to good receptor sensitivity but it was their lower atomic numbers in relation to calcium tungstate that was a major factor. The lower atomic numbers placed their photo-electric absorption K edges at lower energies as illustrated in Figure 17.

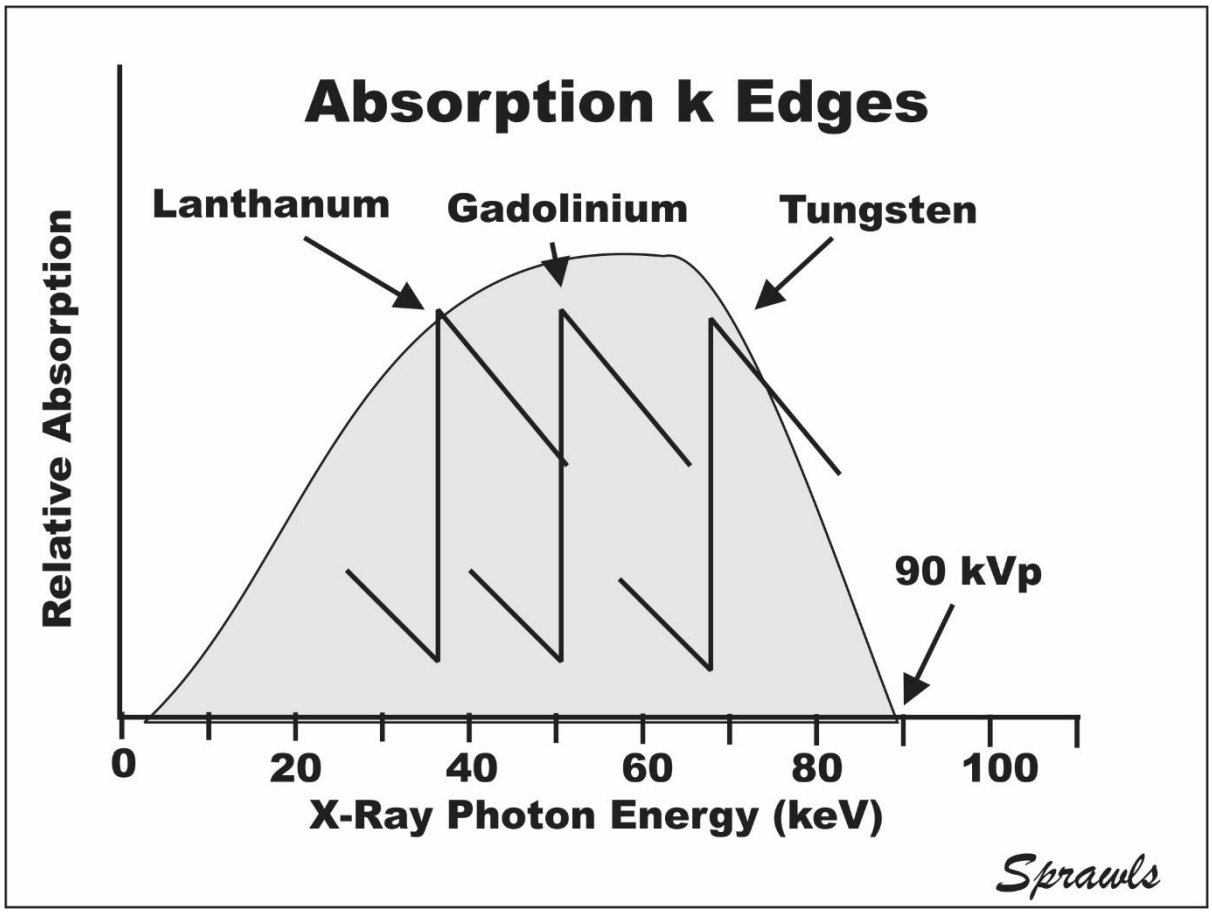

Figure 17. Intensifying screen material absorption **k edges** relative to x-ray spectrum produced at 90 kVp.

A major advantage in transitioning to the rare earth elements for intensifying screens was the increased absorption compared to calcium tungstate. Now the same absorption efficiency could be achieved with thinner screens that produced less blurring and better image detail with less exposure.

11. Advances in Film Science and Technology

Throughout the history of film-based radiography the basic photographic process using silver halide crystals continued. However, research and development continued to produce many advances in design and optimizations for a variety of clinical applications

A major film design change was required with the introduction of rare earth screens. The rare earth screens produced light in the green spectrum and different from the blue light produced by calcium tungstate. The green-sensitive film for use with rare earth screens also required changes in the color of the safe lights used in darkrooms for film processing.

12. The Final Radiographic Receptor Design and Characteristics

Film-screen radiographic receptors benefited from many advances and innovations for over a century to achieve the major goal of higher image quality with lower radiation exposure. However, with the development of digital technology the several limitations of film-based radiography contributed to its decline as a practical diagnostic procedure. The advantages provided by digital radiography were many. A major one was the elimination of the large quantities of film that required manual handling beginning with the loading into the receptor cassettes, chemical processing, arranging for viewing by radiologists, storage and archiving where they could be retrieved. Moreover, film radiography was subject to errors in exposure and variations in the chemical processing that produced problems with image quality. These were greatly reduced with digital imaging. A specific factor was when an image was captured on film and chemically processed it could not be adjusted or changed. With digital radiography the recorded image can be electronically processed to produce an image for viewing with optimized characteristics, especially contrast, for all clinical procedures. And perhaps the greatest advantage is that digital radiographs can be stored, retrieved, and transmitted to other locations for viewing very quickly.

At the conclusion of the film-screen era as the major type of radiographic receptor, the medical profession had a choice from a variety of film-screen combinations. This provided the opportunity to select a receptor with quality characteristics (contrast, blur/detail, and noise) that was optimum for specific clinical procedures, ranging from chest radiography to mammography, and could be balanced with the radiation exposure required to deliver the necessary image quality.

Of the two components of a receptor, film and intensifying screens, film was the major consumable produ

ct and financially significant for both the film industry and the medical facilities. It was generally an expensive product, partially because of its silver content and precise production conditions, and it was a consumable product that could be used only one time. For the most part, the providers of radiographic receptors were industrial organizations with a history and experience in the development and manufacturing of film for photography and photocopying purposes. These included *Kodak*, *DuPont*, *Fuji*, *Agfa*, and *3M*. They also produced intensifying screens that were compatible with the film and provided a choice of image characteristics.

As the major film-screen era was coming to a close and giving way to digital receptors several of the companies attempted to develop those products, but with marginal success. It was the equipment companies that had the technical background and experience and also the digital receptors were often just another component of the imaging systems. Also, since film and processing chemistry was a large consumable market that contribute to the success of the film companies that was no more.

Table 1 illustrates the range of receptors available from one provider, *Kodak*.

The names for the various receptors are the manufacturer's brand or trade names. They do give some indication of the general characteristics.

The inverse relationship between blur (image detail) and sensitivity (speed) is demonstrated here. This is for the most part determined by the thickness of the intensifying screens. Also shown is that receptors using some specific intensifying screens, for example *LANEX Medium*, can have several different sensitivity (speed) values depending on films they are used with. It is the sensitivity or speed of the film that affects the level of quantum noise. Using a higher speed film reduces patient exposure but at the cost of increased noise.

The receptors for mammography were single thin screens combined with film with emulsion on just one side. This was to produce images with very small blur values to provide better visualization of the very small calcifications that are valuable signs of some breast cancers. However, the required exposure, receptor sensitivity, is much greater that for other radiographic procedures.

In summary, over more than a century, film-based radiographic receptors evolved from a simple photographic emulsion on a glass plate to an extensive collection of film and screen combinations to choose from. The many innovations and developments greatly increased image quality with reduced x-ray exposure. The choice among the different combinations as illustrated in Table 1 provided the opportunity to select receptors that were the most optimum for various clinical requirements.

Receptor (KODAK Screen/Film)	Representative Equivalent Blur Value (mm)[1]	Relative Speed [2,3,4,5]	Approximate Receptor Sensitivity[6] (MR)
General Radiography [2,3]			
LANEX Fast/Ortho G, L, C	0.76	600	0.21
LANEX Fast/T-MAT H/RA	0.66	1200	0.10
LANEX Fast/T-MAT G/RA, L/RA, S/RA	0.66	600	0.21
LANEX Regular/Ortho G, L, C	0.64	400	0.32
LANEX Regular/T-MAT H/RA	0.53	800	0.16
LANEX Regular/T-MAT G/RA, L/RA, S/RA	0.53	400	0.32
LANEX Regular/T-MAT C/RA	0.53	400	0.32
LANEX Medium/Ortho G, L, C	0.55	250	0.51
LANEX Medium/T-MAT H/RA	0.44	600	0.21
LANEX Medium/T-MAT G/RA, L/RA, S/RA	0.44	300	0.43
LANEX Medium/T-MAT C/RA	0.44	250	0.51
INSIGHT HC/INSIGHT Film[7]	0.28	350	0.37
INSIGHT Standard/INSIGHT Film[7]	0.28	250	0.51
Extremities [2,4]			
LANEX Fine/Ortho G	0.41	80	1.60
LANEX Fine/T-MAT G/RA	0.23	80	1.60
LANEX Fine/EKTASCAN M (single screen)	0.14	40	3.20
Mammography [5]			
MIN-R/MIN-R M	0.14	100	16.0
MIN-R/MIN-R E (extended cycle)	0.14	150	10.7
MIN-R/MIN-R H	0.14	160	10.0

[1] The equivalent blur value is a measure of the amount of image blurring produced by the receptor. It is similar, in effect, to focal-spot size with respect to determining visibility of anatomical detail. Values are determined from MTF data measured in the laboratory.
[2] Medium-speed calcium tungstate screens and KODAK X-OMAT RP Film are arbitrarily assigned a speed of 100.
[3] Relative speeds are based on the average value of radiographs of three phantoms: (1) pelvis at approximately 70 kV without scatter; (2) chest at approximately 80 kV with scatter; and (3) chest at approximately 125 kV without scatter.
[4] Based on radiographs of an extremity phantom exposed at approximately 60 kV with scatter.
[5] Determined from matched density radiographs of a breast phantom, molybdenum target tube, 28 kVp, single MIN-R Screen/MIN-R M Film arbitrarily assigned a relative speed of 100.
[6] Based in part on Sprawls, P. Jr.; *Physical Principles of Medical Imaging*, Rockville, MD, Aspen Publishers, Inc., 1987.
[7] Determined at density 1.8.

Table1. Film-screen combinations arranged by image quality characteristics and exposure requirements.

Chronology: A Century of Radiography Receptor Developments in Review

Before the Discovery

The discovery of "a new kind of radiation", x- or Roentgen radiation, as it was to become known, followed by the intense research by Roentgen in 1895 demonstrated the capability to image the anatomical structures within the human body and gave birth to the practice of medical radiography. Its rapid spread to other institutions and countries was possible because the necessary technology, including photography, fluorescent materials, evacuated glass tubes for electrical experiments, and high-voltage sources had been developed and was available. This was the foundation on which radiography was built and enhanced over the next 100+ years.

1890s

This was a landmark decade for radiography. Roentgen discovered x-rays and demonstrated the process of radiography. Carl Schleusner manufactured the first glass plates for radiography. *Koda*kintroduced first paper for x-ray purposes and Thomas Edison recommended calcium tungstate for fluoroscopic screens. Michael Pupin reported screen-film radiograph and May Levy made radiographs using double emulsion coated film between two fluorescent intensifying screens

1900s

Glass plates produced for general photography were the available receptors for radiography but their limitations, requiring high x-ray exposure and image quality defects, was a continuing concern.

1910s

During this period the industry was continuing the development and manufacturing of plates designed for radiography that contained emulsions with increased absorption of x-radiation and required less exposure. *Kodak* Introduced film on a flexible cellulose nitrate base and also double emulsion film. Carl V. S. Patterson developed fluorescent intensifying screens with improved characteristics to overcome many of the problems experienced with earlier attempts to use screens. He also introduced the cassette using two screens with double emulsion film.

1920s

The *Patterson Screen Company*introduced fluorescent screens with protective coating for cleaning. *Kodak*introduced film with cellulose acetate base to improve fire safety.

1930s

*DuPont*introduced an x-ray film with blue tinted base to improve viewing comfort that became the standard type of film throughout the industry. *Patterson Screen Company*introduced *Patterson Par Speed screens*. This became the reference to which other screens were compared. *Ansco*introduced a direct x-ray exposure film for some specific clinical applications. *Fuji* began producing x-ray film.

1940s

*Pako*introduced an automatic film processor that mechanically dipped sheets of film into the series of processing solutions.

1950s

*Kodak*introduced the roller transport process in which film was moved continuously through the several processing steps…a major innovation.

1960s

DuPont made first film on a polyester base that was more flexible and had other desirable properties. *Kodak*introduced a rapid process (90 second) film development system

1970s

This will probably go down in history as the second most significant decade in the development of screen-film radiography. Being second to the 1890s when it all began. It was the transition from calcium tungstate to rare earth intensifying screens with several related innovations. *Kodak*introduced ultraviolet emitting screens which reduced light crossover. *3M* entered the radiography market with the Introduction of rare earth screens and low crossover film. A high-detail intensifying screen and a single emulsion film designed specifically for mammography was introduced. This began the transition of breast imaging from film exposed directly by x-radiation and a significant decrease in radiation dose to the patient.

1980s

With most of the industry now converted to rare earth intensifying screens there were some continuing developments to enhance image quality. Special emphasis was given to reducing light crossover through the film base that reduced image detail. Methods included a tabular (flat) grain replacing the more cubic grain in the emulsion and designing base materials with increased absorption of the light spectrum, especially in the ultraviolet, emitted by the screens.

During this decade radiography receptors using digital technology began to replace film using the chemical photographic process. It was the beginning of the end of the era in which radiography developed as a major medical procedure by extending conventional film-based photography to visualize the interior of the human body.

A. Acknowledgment

The history of x-ray imaging has been researched and documented by many and their contributions are referenced in the following bibliography. Special recognition is extended to friend and medical physics colleague, Arthur G. Haus. In addition to his career contributions to the development and application of radiographic receptors, especially film, his extensive research on the history of x-ray imaging is published as indicated in the review articles below and provided valuable resources for this manuscript..

Bibliography

These publications provide extensive information and details on the scientific and technical development of radiography and related clinical applications, especially for the long era when film was used for both the receptor recording medium and display for viewing. Each publication generally gives emphasis to a specific perspective of the historical development and provides a comprehensive coverage. To guide additional reading and research the publications are organized in specific categories. These are Roentgen's Research, History Books, Historical Review Articles, and Research Reports on Specific Developments and Applications.

Roentgen's Research

RoentgenWC. Ueber eine neue art von strahlen. (ufige Mittheilung.)
Sitzber, *Physik-Med Ges Wurzburg*. 1895; 9:132-141.

This was the first of four publications by Roentgen describing his extensive research following the discovery of "a new kind of radiation". These publications have been translated into English and published along with details of Roentgen's life and career in the following.

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HISTORY OF MEDICAL PHYSICS E-LEARNING INTRODUCTION AND FIRST ACTIVITIES -IOMP HISTORY OF MEDICAL PHYSICS

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Content

Medical Physics was one of the first professions to develop and introduce e-learning. This was underpinned by the need of extensive imaging material and specific explanations for the professional education and training. The process was additionally supported by the excellent computer skills of the majority of medical physicists.

The introduction of e-learning in Medical Physics happened before the existing of the term. Initially (in 1994) the e-learning materials were named "electronic teaching materials" and "multimedia". The term "e-learning" emerged in 1998 through the paper of A Morri in Connected Planet (Nov 1997) "*A bright future for distance learning: One Touch/Hughes alliance promotes interactive 'e-learning' service'* ".

The global development of e-Learning started some 20 years ago, hence most of the results and processes are quite recent. These also develop with high speed and often the full development is difficult to be followed. Judging by the large number of e-learning projects in medical physics, one can be sure that this field will have significant development in future and will play an important role in the global professional growth.

1. The Introduction of e-Learning in Medical Physics

The development of e-learning in medical physics has been a pioneering process, triggered by the very dynamic nature of the profession. The existing before the 1990s paper print was slow and not able to answer the very fast development of various medical equipment and related methods. The new Desk-top Publishing (DTP) methods offered an answer to this problem. This is how a sequence of 4 international projects introduced e-learning in medical physics (EMERALD, EMERALD II, EMIT and EMITEL), these projects were interlinked with 3 other international educational projects, thus forming a sequence continuing 20 years, which encouraged many other e-learning projects in the profession. Detailed description of these projects is available in the free e-book "The Pioneering of e-Learning in Medical Physics" [1]. The very innovative work on e-learning in medical physics, and its global impactresulted in the inaugural award for education of the European Union – the Leonardo Da Vinci Award (2004), what was important for the visibility of the profession.

1.1 Pilot Project EMERALD and its Image Database (IDB) - the second IDB in the world with ISBN

The concept of a project related to electronic teaching materials (later to become the pilot project EMERALD) was introduced in 1989, but the actual project was developed by S Tabakov during 1994 and was later submitted for support to the European Union (EU) programme Leonardo. This pilot project was orientated towards development of electronic materials for medical physics training (the term 'e-learning' did not yet exist).

The partners in the project were a Consortium of Universities and Hospitals from UK, Sweden, Italy and Portugal: King's College London - School of Medicine and Dentistry, University of Lund, University of Florence, King's College Hospital, Lund University Hospital, Florence University Hospital, The Portuguese Oncological Institute in Lisbon, the High School of Medical Technology Lisbon and the International Centre for Theoretical Physics (ICTP) in Trieste, Italy. Project Contractor

was Prof V C Roberts, Coordinator was Dr S Tabakov and representatives of the Partners were: Prof S-E Strand, Prof J Gomes da Silva, Prof F Milano, Dr C A Lewis, Dr I-L Lamm, Dr A Campagnucci and Dr A Benini.

The project was managed and co-ordinated by King's College London and was supported by the European Federation of Organisations for Medical Physics (EFOMP), the European Association of Radiology (ESR), the International Atomic Energy Agency (IAEA) and the Medical Physics Societies of the partner countries.

The objectives of EMERALD (acronym of: European Medical Radiation Learning Development) were: "Development of common vocational training modules in medical radiation physics, which will incorporate materials for distance learning on CD and multimedia". The initially planned 3 modules were: Physics of X-ray Diagnostic Radiology, Physics of Nuclear Medicine, Physics of Radiotherapy.An additional module was also planned (Physics of Medical Imaging), but it was decided that it will be developed in future as a separate project (what later became the basis of project EMIT). The approved length of the project was 3 years.

The main tasks in the project were:

- Structuring the Syllabi of the training modules (i.e. Training Timetables)
- Preparation of the Training Workbook concept
- Preparation of Students' Manuals (Workbooks with Training tasks) for each module
- Preparation of Teachers' Guide
- Preparation of CD Image Database (IDB)
- Evaluation of the modules
- Introduction of the modules with manuals, guides, CD image database.

The EMERALD training tasks were based on the concept "learning through examples" and were similar in structure to University 'Lab Manuals'. The description of the Training tasks was made in tables and it was decided that the main competencies (achieved after completing of certain tasks) will be based on the earlier published IPEM competencies (IPEM – the UK Institute of Physics and Engineering in Medicine). The indicative time (days) for acquiring a certain competency was to be based on practical performance of the tasks and further time for adding a written description of these - i.e. preparing part of the Training portfolio (Fig.1).

Each of the three Training Modules incorporated:List of Competencies, in accord with the UK Institute of Physics and Engineering in Medicine (IPEM) Training scheme at the time; Structured Timetable (Syllabus with the approximate time necessary for each task); Student Workbook with Training tasks (performance of each task leads to certain competency); CD-ROM with Image Database (to facilitate the teaching process) [2].

Typical structure of an EMERALD Training task has the following sub-sections:

-Task name and aim
-Competencies addressed
-Equipment and materials
-Procedures and Measurements
-Results (Calculations, Diagrams, etc)
-Observations, Interpretations, Questions, Conclusions
-Reference documents
-Verification (the completion of each task requires verification by the Teacher/Trainer).

No.	Sub-module and Subject	Necessary materilas/arrangements	Competencies acquired	Days	Comments
5.x	**X-ray tube and generator**		**Understand/measur / compare separate X-ray tube/gen. parameters *(2,3,4,5,14,15,22)**	7	
5.1	X-ray tube Components. X-ray tube Characteristics. Loading diagram of a X-ray tube. Some typical X-ray tube characteristics. Special X-ray tube types.	X-ray tube diagrams; Different company brochures; Several types tube inserts	Understand/compare X-ray tube paramet.	2	
5.2	Tube housing - construction. X-ray beam filtration. Light beam diaphragm. HVL measurement. Estimating the total filtration from the HVL. Shielding, leakage radiation.	Tube housing; X-ray radigr. room; Dosemeter; Al plates HVL/Filt. diagrams; ~6 X-ray film/cassettes	Understand/measure X-ray tube filtration	1	Repeated in No.7 as part of a whole QC test
5.3	X-ray tube output parameters (consistency, output variation, linearity). Typical parameters. Factors affecting tube output. X-ray tube output spectrum and distribution. Measuring of the focal spot . Assessing the beam alignment. Seasoning of a new X-ray tube . X-ray tube failure.	X-ray radiogr. room; Dosemeter; calculator, Foc. spot meas. tool; LBD align. tool	Understand/measure /calculate tube output param., focal spot size and LBD. Learn to season the tube	2	same

Fig. 1 EMERALD Training Timetables (Training Curriculum) – sample from Diagnostic Radiology module – submodule with Training tasks related to X-ray tube assessment.

To support the teaching/training process EMERALD Consortium developed an electronic Image Database (IDB) [3] (first on CD-ROM, and later on web site, as part of another project - Emerald II).

The main types of images in the Image Database were:

-Equipment and its components; Block diagrams and graphs; QC procedures and measuring equipment; Test objects and image quality examples; Typical clinical images and artefacts, etc.

The organization of images in folders followed the organization of the Training tasks. The volume of the three IDB was about 1400 images.

Each IDB (for each module) was engraved on a CD-ROM. A PC type image browser (*ThumbsPlus*by *Cerious Software*) was used for quick and easy search through the IDB on the CD-ROM. The browser presents each image as a slide, which can be further viewed in its original JPEG size. Each image is visualised with a corresponding caption, on which basis a Keyword search can be performed (Fig. 3).

At that time CD-ROMs were not assigned ISBN (International Standard Book Number). Even the important paper book "Electronic Publishing on CD-ROM" by S Cunningham and J Rosebush (O'Reilly & Associates Inc, ISBN 1-56592-209-3, published in 1996) had an ISBN for its paper version, but not for its accompanying digital copy on CD-ROM – an excellent early PDF e-book. The popular at the time Microsoft ENCARTA Encyclopaedia was also without an ISBN.

The very small number of electronic books issued on CD-ROM at the beginning of the 1990s used ASIN numbers (Amazon Standard Identification Number - a 10-characters identifier of Amazon) after 1994, instead of ISBN numbers. After 2000 all e-books and other digital materials use unique ISBNs. Even an e-book with different formats (for different e-book Readers) is required to have different ISBNs for each format.

The new electronic media carriers (e.g. CD-ROM) contained the same information as print media (paper books), surpassing them in potential volume, image quality and cost-effectiveness. Due to this reason it seemed logical to the EMERALD Consortium that these carriers have the same identification, ISBN, as printed books. This way during 1997 the Consortium decided to publish the first ready Image Database with its unique ISBN. By that time one of the three volumes of the Image Database was fully completed - the X-ray Diagnostic Radiology (for this task special help was received by the colleague A Litchev from the parallel educational project ERM in Plovdiv).This way the IDB X-Ray Diagnostic Radiology was published on 19 February 1998 - EMERALD Image Database version a.01, 1998 , ISBN 1 870722 03 5 (Fig.2). Later the two other IDB (on Nuclear Medicine and Radiotherapy) were also published with unique ISBNs.

IDB related to X-Ray Diagnostic Radiology is one of the first 3 IDB on CD-ROM with ISBN in the world:

-Atlas of Pathology: Urological Pathology CD-ROM, 30 Dec 1997, Springer-Verlag, ISBN 3540146571

-EMERALD Image Database, Training Courses in Medical Radiation Physics CD-ROM, 19 February 1998, King's College London, ISBN 1870722035

-Developmental Psychology Image Database CD-ROM, 30 April 1998, McGraw-Hill, ISBN 0072896914

To our knowledge these are the world's first ISBN-numbered electronic Image Databases (on CD-ROM) as well as one of the first ISBN-numbered e-learning materials. The profession can be proud that EMERALD was one of the first such products in the world.

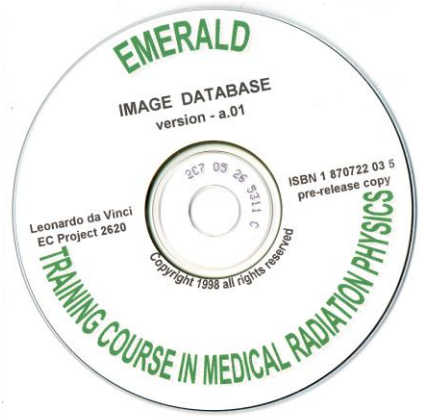

Fig. 2 The first CD with EMERALD Image Database

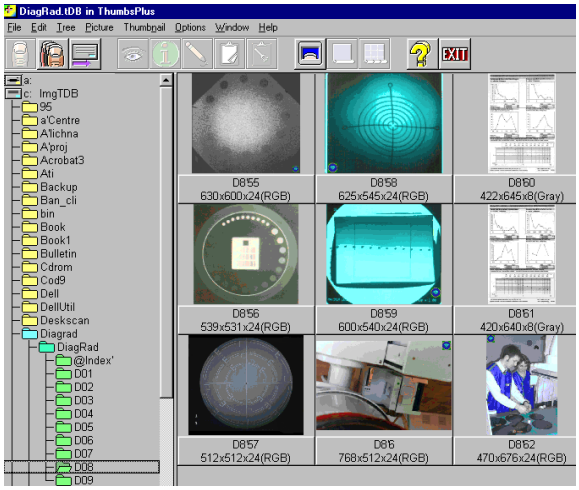

Fig. 3 The Interface of the Image Database with thumbs (slides) foreasy finding of each image. The Folders with images correspond to the Workbook chapters - a sample from the hard drive source

These materials and the IDB were new and no experience existed on their practical use. Due to this reason a Teacher's Guide was developed. The Content of the Course Guide included:

-Introduction to EMERALD project
-Trainees and Training scheme
-Training Agenda
-Mutual Intent
-Continuous Assessment
-Feedback on Placement and Manuals
-Training Timetables (full Training Syllabus)
-Principles of Radiation Protection and Risk Assessment
-EURATOM 96/29 and 97/43 Directives implementation
-EMERALD Forms (Training agenda, Statement of Mutual Intent; Safety; Continuous assessment; Feedback)
-APPENDICES (Training Portfolio; End point viva; Cheating and plagiarism).

To assess these first e-learning materials a special Conference was organised at ICTP Trieste. The EMERALD Conference (24-26 September 1998) was organised under the banner "The First International Conference on Medical Physics Training". It included experts from 26 countries, as well as EFOMP Officers. Each delegate received a copy of the Training materials and the CD with the Image Database. The three EMERALD modules were assessed and reported in separate Workgroups of experts. One important element of the Conference was the presence of young colleagues (students and trainees) who had tested the materials. They were included in each of the three training module groups. The Conference delegates strongly supported the practical implementation of the EMERALD e-learning materials [4].

The whole assessment process was initiated well before the Conference and included several levels:

-First level – the Training tasks (developed by various specialists) were exchanged and discussed internally inside the Project Workgroups;

-Second level – each Group of tasks was evaluated as an entity by the Workgroup (additionally young colleagues, who had just completed their training, were asked to check their cohesion).

-Third level – the Groups of tasks were exchanged between the different international Workgroups

-Fourth level – External Assessors were appointed to provide independent review of the products

-Fifth level - full Training module (all tasks) was tested by un-trained graduates

-Sixth level – an International Conference of experts was organised to comment on the tasks from the point of view of their use in various European countries (this being an EC project)

-Seventh level – based on the feedback above the materials were edited by the Workgroups and the final product was again seen as a totality by the Consortium and the External Assessors.

Following this Conference the EMERALD materials and their respective CD-ROMs were released as the first e-learning in the profession. These entered quickly the training activities in many countries and are now used in nearly 100 countries, covering almost all low-and-middle-income (LMI) countries. The tasks of the modules were developed in a way to be used also as stand alone materials, this way the tasks which were outdated dropped out of use, while others continue to be used for more than 20 years. The development of the first e-learning materials was so intense and dynamic, that most of the detailed publications about them were made after the completion of the projects [5,6]

In 1999 most of the materials from the EMERALD project were transferred into the first educational web site in the profession www.emerald2.net (currently www.emerald2.eu), what will be described further down. The international use of these materials and their impact for the profession will be described later in this chapter.

The content of all 3 modules and its tasks can be seen at the EMERALD and EMIT web site [7].

Module 1 - "X-ray Diagnostic Radiology Physics" was developed mainly by the UK partners. In included 49 Training tasks in the Diagnostic Radiology (DR) Physics Workbook, grouped in 10 chapters (in 2002 a new chapter with tasks related to Digital Radiology was added).

Module 2 - "Nuclear Medicine Physics" was developed mainly by the Swedish partners. It included 46 Training tasks in the Nuclear Medicine (NM) Physics Workbook, grouped in 15 chapters.

Module 3 – "Radiotherapy Physics" was developed mainly by the Italian and Portuguese partners (with input from Swedish partners specifically for Brachytherapy). It included 48 Training tasks in the Radiotherapy Physics (RT) Workbook, grouped in 21 chapters.

The following ISBN numbers were assigned to the EMERALD materials:

PRINTED

1. Workbook on Physics of X-ray Diagnostic Radiology : ISBN 1 870722 04 3
2. Workbook on Physics of Nuclear Medicine : ISBN 1 870722 05 1
3. Workbook on Physics of Radiotherapy: ISBN 1 870722 06 X
4. Course Guide: ISBN 1 870722 07 8

ELECTRONIC (CD-ROM)

5. Image Database vol.1 - Physics of X-ray Diagnostic Radiology: ISBN 1 870722 03 5
6. Image Database vol.2 - Physics of Nuclear Medicine: ISBN 1 870722 08 6
7. Image Database vol.3 - Physics of Radiotherapy: ISBN 1 870722 09 4

The EMERALD Consortium developed three Training modules, each including specific Workbook with Training tasks and Image Database. The completion of each module requires 4 months (80 days). During this time the trainee is expected to acquire most necessary professional skills. This part of the training was called "condensed" and can be performed in most countries, where training conditions exist. Further the trainees can spend several months in their country/state where they can additionally study local Regulations and professional requirements.

Each of the three modules is based on Training tasks. Each task was given a notional completion time (in days). To achieve completion of all three modules in a period of 1 year would require very intensive work. However the design of the EMERALD scheme would allow the individual modules to be taken separately with intervals between each. The overall volume of the printed materials (tasks and guide) was c.720 pages, the overall number of images associated with the electronic teaching materials was 1400.The initial distribution of these materials on CD was later replaced with e-learning materials on the Internet [7] from 1999 (please see further down).

1.2 Project EMIT and the first Conference on e-Learning in Medical Physics

In 2001 the EMERALD Consortium expanded and developed a new project – EMIT (acronym of: European Medical Imaging Technology Training). The project EMIT was developed as a continuation of project EMERALD. Its main aim, as per the EC application was to use the original e-learning platform of EMERALD for adding two new Training modules related to Medical Imaging - Magnetic Resonance (MRI) and Ultrasound Imaging (US).

The Consortium included as partners: King's College London - School of Medicine and Dentistry; King's College Hospital Healthcare Trust; University of Lund; Lund University Hospital; University of Florence; Florence University Hospital; Hospital Albert Michallon, Grenoble; the European Federation of Organisations for Medical Physics (EFOMP). This was the first EC project for EFOMP, which paved the way for future European projects for the Federation. Later the project was joined by two more partners: the International Centre for Theoretical Physics (ICTP), Trieste, Italy and the Tempus ERM Medical Radiation Physics Centre in Plovdiv, Bulgaria (part of Medical University Plovdiv).

The new expert colleagues, who joined the project Consortium were: Dr A Simmons, Dr S Keevil, Dr C Dean, Dr D Goss, Dr V Aitken, Dr R Wirestam, Prof. F Stahlberg, Dr M Almqvist, Dr T Jansson, Dr J-Y Giraud. As in the EMERALD, Project Manager was Prof C Roberts, and project Coordinator was Dr S Tabakov. The approved length of the project was two years and a half (it was later extended to 33 months).

The EMIT project followed the same methodology, structure of training tasks and IDB as project EMERALD. It included additionally some simulation and interactive training tasks.

The materials of EMIT were also assessed, using similar methodology as for EMERALD [8]. A special EMIT Conference was organised under the banner "The First International Conference on e-Learning in Medical Physics" (Fig.4). The Conference included project partners and representatives from IOMP and IFMBE (the International Federation on Medical and Biomedical Engineering). The venue of the Conference was in ICTP, Trieste (9-11 October 2003). At the Conference all delegates signed a Declaration where they expressed their intent to collaborate in the future development of education/training and e-learning materials (Fig.5).

The project EMIT developed two training modules (on MRI and Ultrasound Medical Imaging) each with a common length of 4 months (80 days) – as in project EMERALD. During this time the trainee would have to acquire most necessary professional skills - this is the "condensed" part of the training which can be performed in most countries where training conditions are set up. Further the trainees can spend up to 2 months in their own country/state where they can additionally study the local Regulations and professional requirements.

The content of the two modules and its tasks can be seen at the EMERALD and EMIT web site [7].

Most of the modules were developed by the UK and Swedish partners, with input from the other partners.

The Module "Diagnostic Ultrasound Imaging Module" included 54 Training tasks (327 pages), grouped in 21 chapters. This module also included tasks for sonographers.

The Module “Magnetic Resonance Imaging” included 50 Training tasks (185 pages), grouped in 19 chapters. This module also included simulations and spreadsheets with imaging data to support the training.

The following ISBN numbers were assigned to the EMIT materials:

EMIT Training Course Guide (incl.Curricula)	ISBN 1 870 722 15 9
EMIT Training Workbook (e-book) on Ultrasound Imaging	ISBN 1 870 722 19 1
EMIT Training Workbook (e-book) on MRI Imaging	ISBN 1 870 722 18 3
CD-ROM EMIT Image database on Ultrasound Imaging	ISBN 1 870 722 17 5
CD-ROM EMIT Image database on MRI Imaging	ISBN 1 870 722 16 7

Additionally the above Training modules were published as web-based e-books and engraved together with the Image database on two CD-ROMs (one for each module).

The MRI e-book and IDB CD-ROM structure includes about 4600 files.

The Ultrasound e-book and IDB CD-ROM structure includes about 8900 files.

CD-ROM EMIT – Ultrasound Imaging (Guide, e-book, IDB)	ISBN 1 870 722 14 0
CD-ROM EMIT – MRI (Guide, e-book, IDB)	ISBN 1 870 722 13 2

Both combined CDs were published on 13/8/2004. The EMERALD materials were re-produced in a similar way. The final CDs and the structure of one CD are shown on Fig.8.

Fig. 4 Delegates at the EMIT International Conference on e-Learning in Medical Physics, ICTP, Trieste, 2003

Conference Participants: Prof.R Stollberger, Dr M Stoeva. Dr R, Dr P Kaplanis, Prof. L Musilek, Dr A Paats, Prof. V Poutanen, Dr S Naudy, Dr C Étard, Dr E Perrin, Dr A Briguet, Prof E Rosenfeld, Dr G Helms, Prof J Nagel, Dr T Sioundas, Dr P Zarand, Prof M Bracale, Dr C Bigini, Dr F Fidecaro, Prof. L Bertocchi, Dr G Boyle, Mr L Torres, Prof. A Lukoshevicius, Mrs V Gersanovska, Dr C vaan Pul, Prof. M Radwanska, Dr N Teixeira, Dr K Nagyova, Dr A Millan, Dr I Hernando, Prof Y Ider, Dr A Krisanachinda, Prof P Sprawls, Dr S Keevil, Dr C Oates, Dr A Evans, Dr N Fernando, Prof. C Roberts, Dr S Tabakov, Dr C Lewis, Dr V Aitken, Dr C Deane, Dr D Goss, Ms G Clarke, Dr A Simmons, Dr I-L Lamm, Dr R Wirestam, Prof F Stahlberg, Dr M Almqvist, Dr T Jansson, Prof. F Milano, Dr J-Y Giraud, Prof. P Smith, Dr M Buchgeister, Mr A Cvetkov, Ms J Young, Ms M Boutros, MsT Wehrle, Ms S Riches

The pioneering work and the impact of these two projects gained the first EU Leonardo da Vinci Award for Education. The Award was presented to the Consortium at the high level EU Conference “Strengthening European Co-operation in Vocational Education and Training”, held in Maastricht, The Netherlands, on 14-16th December 2004 (part of the summit of all European Ministers of Education). This was an excellent opportunity for high visibility of the profession – Fig 7.

Fig.7 The Leonardo da Vinci Award Certificate

DECLARATION OF INTENT

We all participants at the European Conference on Medical Physics Training (Magnetic Resonance and Ultrasound Imaging), organized by EU Leonardo Project EMIT at the Abdus Salam International Centre for Theoretical Physics, ICTP, Trieste, Italy (10-11 October 2003), underline the very important role of Medical Physics Training for the effective and safe use of medical imaging equipment in healthcare.

The education and training in Medical Physics is vital for the development of healthcare and we highly appreciate the activities of the European Union, IAEA, ICTP, IOMP, IFMBE, EFOMP and other international and national institutions in this direction.

We declare our intend to collaborate in the development of various initiatives in education and training, including e-Learning, related to medical technology (in its medical physics, medical engineering and medical application aspects), which will complement and integrate existing programmes. In this connection we agree to form a Network, which will facilitate our aim to harmonise activities and opportunities available to students and colleagues working in healthcare throughout Europe and other countries.

11 October 2003
ICTP, Trieste

Signed by: Representing:

Fig. 6 Main (first) page of the Declaration of EMIT Conference on e-Learning in Medical Physics.

Fig. 8 EMERALD and EMIT CD-ROMs with sample CD jewel boxes (and CD covers). The content of one CD (DR) is shown on the left, including the IDB (folder DiagRad) and the Web site with e-books (folder Emerald2)

Additionally to the e-learning materials project EMIT developed the first Medical Physics Thesaurus and Dictionary of Terms, which gave the basis of the later project EMITEL, which developed the first Medical Physics e-Encyclopaedia and Multilingual Dictionary (translated by 2017 to 29 languages). These will be described further down.

The initial e-learning materials (Training Tasks and IDB) developed by project EMERALD, and the following project EMIT,were transformed into new 5 CD-ROMs including web-based e-books with Training tasks, hyperlinked to the images from the Image Databases. The overall volume of these 5 e-learning modules was 247 Training tasks, supported by 3100 specific educational images[1,3,9]. Each of the new CDs also included the first Medical Physics e-Dictionary of Terms (in 7 languages at the time).About 5,000 of the CDs with these materials were produced and distributed to colleagues in Europe and around the world.

This transformation of the initial EMERALD e-Learning materials into web-based materials was made through the project EMERALD II (described further down). All these e-learning materials were uploaded to a specially made educational website. The e-learning materials of EMIT were also developed as web-based materials and published at this special web site. All these e-learning materials are now available for free use at http://emerald2.eu/cd/Emerald2/.The global use of these e-learning materials, expanded with their online use, will be described further down as part of EMERALD II project.

2. Internet based e-Learning materials and other e-Learning Projects

2.1 Emerald – Internet Issue, the first dedicated education/training web site in the profession

Immediately after the end of the EMERALD project in 1998 its Consortium launched another project aiming to transfer to Internet the Training Tasks and the images from the Image Databases. The project also aimed to disseminate the use of these e-learning materials in Europe and worldwide. The name of the new project was EMERALD – Internet Issue (aka EMERALD II, or E2) For this task the initial Consortium was expanded with new partners from France, Czech Republic, Ireland, Northern Ireland – it included: King's College School of Medicine and Dentistry; King's Healthcare Trust; University of Lund; Lund University Hospital; Portuguese Institute of Oncology, Lisbon; University of Florence; Florence University Hospital; Centre Alexis Vautrin - Nancy; Czech Technical University in Prague; Northern Ireland Regional Medical Physics Agency - Belfast; St James's Hospital, Dublin. Later the Medical Physics Centre ERM from Plovdiv, Bulgaria also joined the project. The new expert colleagues, who joined us were: Dr A Noel, Prof. L Musilek, Dr P Smith, Dr N Sheahan, Dr S Bowring, Dr Stoeva and Dr Cvetkov. As in EMERALD, Project Manager was Prof. C Roberts, and project Coordinator Dr S Tabakov. The approved length of the project was two years (expanded to 2.5 years).

The main drivers for the development of the EMERALD web site were B-A Jonsson and M Ljungberg from Lund [9]. Their University was already firmly on the path of e-learning and they had their own platform for distance learning through Internet – the e-learning management system LUVIT. The new web site was specially coded (www.emerald2.net) [10]. The decision to have a tailor-made web site (i.e. not to use third-party software for development of web-sites) proved to be very important – this web site has now worked for nearly 20 years without any interruption or problem (during 2007 M Stoeva and A Cvetkov re-programmed the web site, keeping its concept, and it now works at www.emerald2.eu).The new web site was made with an uncomplicated user-friendly platform, handling PDF documents and images. This also allowed easy future upgrades of materials – something very important for a dynamic profession as medical physics.

The internal structure of the web site was following the structure of the three EMERALD Training modules. New folders were also added for further video or other materials, which could be included in future to the web site. The web site has about 4000 files organised in 30 folders. These were the new Internet-based e-books of EMERALD. In 2003 the EMITInternet-based e-books were also added to the main web site. The internal structure of one of these e-books can be seen on Fig.8.

The use of these e-books (e-learning training materials) is still the same - it requires simultaneous work with two browser windows (main window and image window). The main window includes a large Text Frame for the PDF file; a Contents Frame for navigation through the training tasks; and an "Image-slide" Frame for browsing the images in each chapter. The additional image window contains the respective image (hyperlinked to the text) and image caption. The images are in JPG format, embedded in separate HTML frames (the image window). When an image is called this window appears (pop-up) over the main window and has its own minimise/close buttons. All functionality of Adobe Acrobat Reader is preserved, allowing saving and printing of each part of the e-learning materials. Also, each image could be saved separately as JPG file. This simplicity allows the users to learn directly -using their own computers with their Internet browser and Adobe Acrobat Reader (without the necessity to install additional software). The Graphical Interface of the e-books is shown on Fig.9.

In order to help distribution of the medical physics e-learning materials into the education/training in the LMI countries (where at the time the Internet was still very slow), the Consortium decided to engrave the whole web site on a CD. This was a very novel idea (invented by the Consortium), but due to the extremely rapid development of the project (alongside all other clinical duties of the project members) this was not published at the time. Later this method (web-site on CD) was widely used in all IT-related developments. These new CDs (one for each module) were described in the previous paragraph.

The new EMERALD II web site was launched at the end of 1999 – this being the first dedicated education/training and e-learning web site in medical physics. The web site continues to be used worldwide with at least 2000 hits per month. The web server official statistic for March 2018 shows total visits 4033 (c.1400 in Europe; c.1400 in Asia; c.700 in North America; c. 250 in South America; c.250 in Africa).

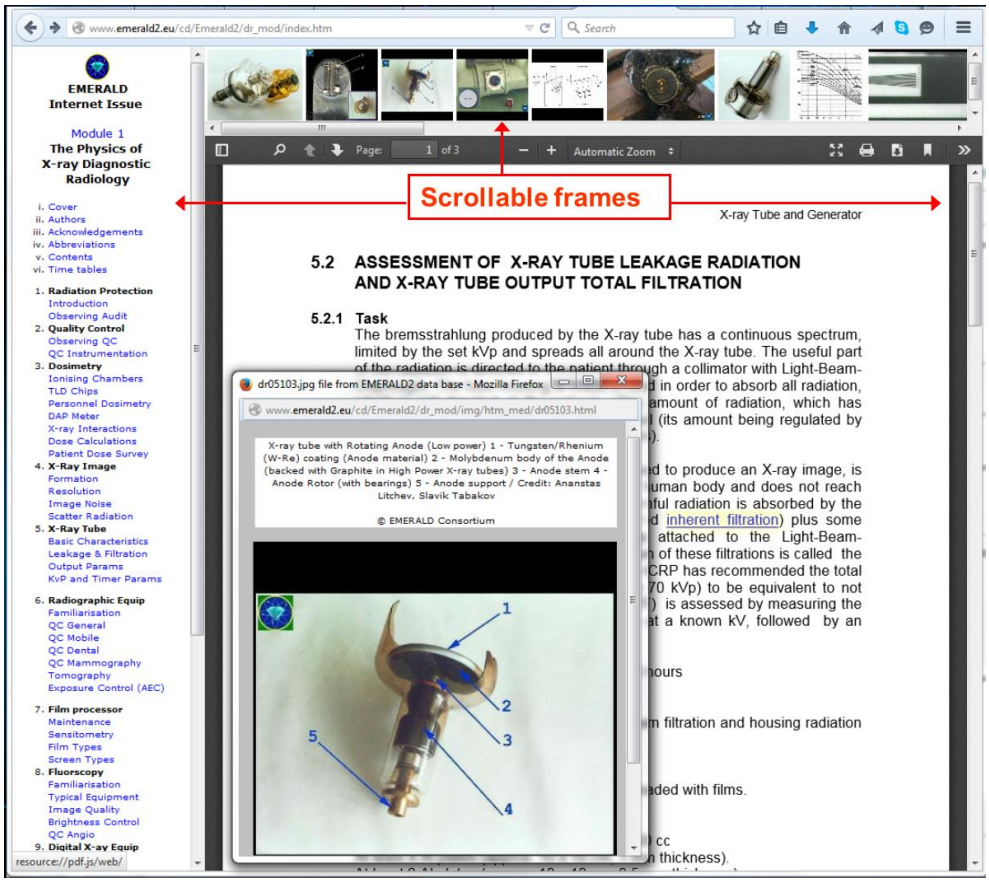

Fig. 9 Screen captures of the EMERALD II e-book (showing the two windows – for text and pop-up image), also showing the 3 HTML frames of the web site.

2.2 The Sprawls Resources

The Sprawls Resources is a very important web-based Medical Physics educational project launched almost simultaneously with EMERALD II and is available on the web at www.sprawls.org/resources. The Resources Project is provided by the Sprawls Educational Foundation, www.sprawls.org. Professor Perry Sprawls was a clinical medical physicist and educator on the faculty of Emory University in Atlanta, Georgia USA. His major emphasis was on developing educational programs and materials to support the effective and safe application of the various imaging modalities, especially Mammography, Computed Tomography and Magnetic Resonance Imaging. It provides a variety of learning opportunities for practicing medical physicists and students in addition to materials to be used by medical physics educators. These include many of Professor Sprawls' lectures, text books (as e-books), materials with medical images, high-quality visuals and additional learning guides including mind maps [11].

The materials are based on Professor Sprawls' approach to learning and teaching which involves helping learners/students develop highly-effective mental structures and representations of medical physics realities and concepts that can then be applied in medical physics activities. This is achieved by providing materials in an organized and structured content with extensive visuals. He promotes teaching as a collaborative process between the provider of resources, especially visuals and textbooks, to be used in classroom activities, and the local teachers who then conduct discussions using the resources and add their knowledge and experience.

Examples are shown in Figures 10 and 11.

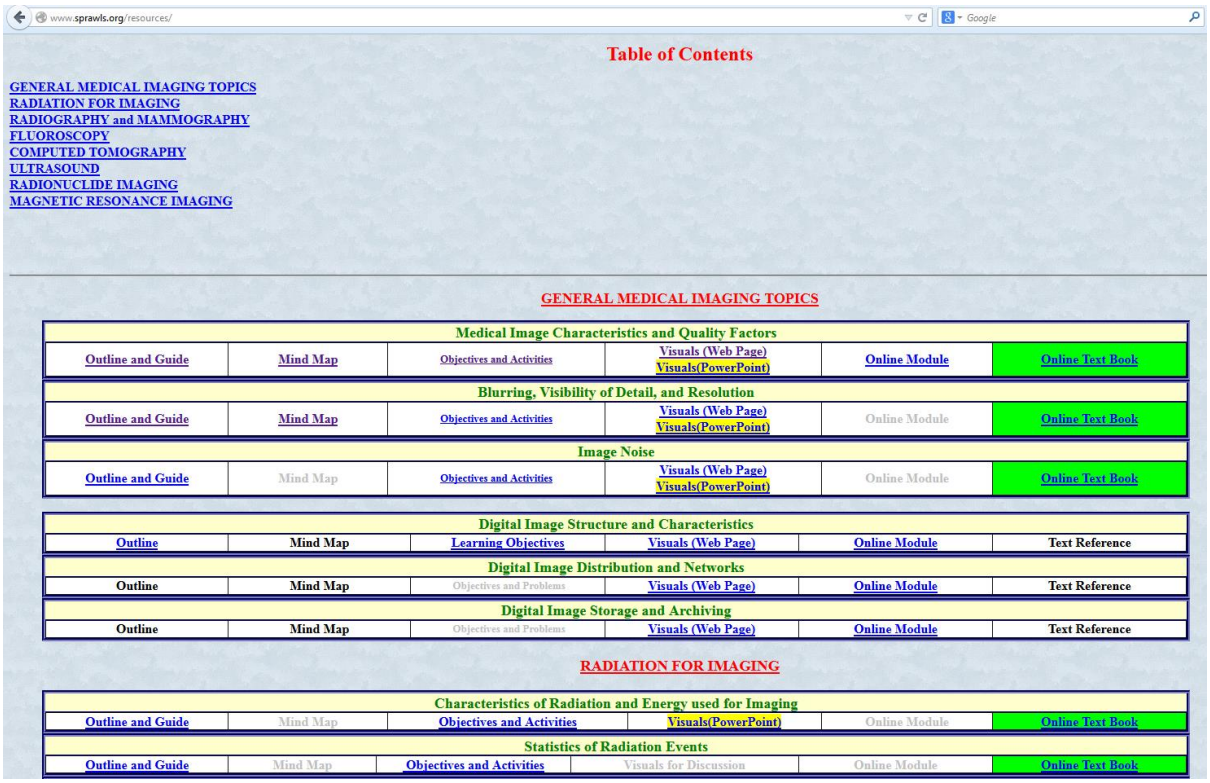

Fig. 10 Sample Graphic interface of P Sprawls's web site (from 2014)

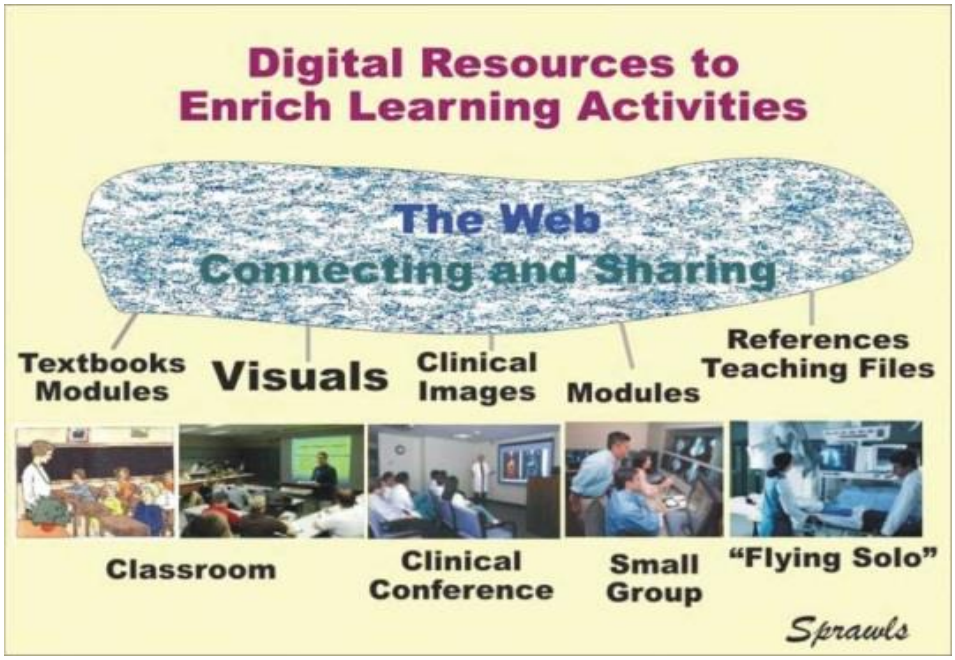

Fig. 11 The many applications of web-based resources to support medical physics education.

This way the learner is easily and effectively guided through the learning process. Sprawls's use of the method for organizing and remembering the material (Mind Maps) is unique for Medical Physics. This web-based resource quickly became one of the most visited educational websites in the profession and is used in virtually every country of the world where there is medical physics activity (Fig.12).

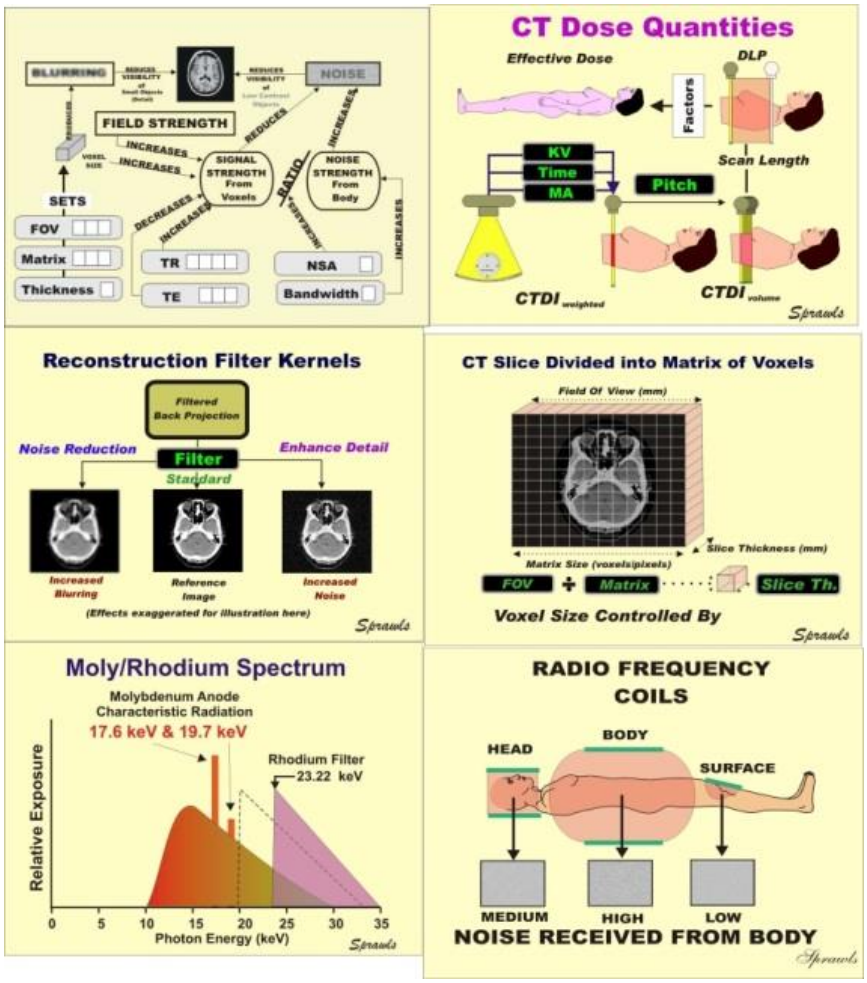

Fig. 12 Example content provided within the Sprawls Resources.

The websites, www.sprawls.org/resources and www.emerald2.eu complemented each other very well – one providing the academic and classroom education activities, the other – the practical tasks (i.e. the training). Both websites (developed fully independently) shared a common vision – simple and effective web shell, whose main function is to deliver the necessary knowledge. Both web sites were intentionally distanced from the most hyped web technologies and placed emphasis on the educational content. Both websites use dedicated programming without any third-party templates. Both websites are run by experts, enthusiastically supporting the development of Medical Physics. Both websites have continued to run for almost 20 years with thousands of visitors. It was only natural to collaborate and indeed Sprawls became one of the main contributors to the later project, EMITEL Encyclopaedia, which incorporated many of the EMERALD&EMIT images and Sprawls' visuals.

One of the most successful global disseminations of e-learning in medical physics was through the ICTP International College on Medical Physics, whose objective is to provide condensed education on medical physics (imaging) to colleagues from low-and-middle-income (LMI) countries. Since 2002 each attendee to this unique summer College receives free all e-learning materials from the web sites sprawls.org and emerald2.eu

The first ICTP College on Medical Physics took place in 1988 - a 4 week activity with nearly 100 participants from the developing (LMI) countries. The regular series of such Colleges started in 1992 and continues to run on a regular basis (usually bi-annually) with similar number of participants. Until now the ICTP has educated more than 1000 young medical physicists - mainly from developing countries (LMI countries). A specific re-organisation of these e-learning materials was made for the College participants – all e-learning was compiled on a single CD (with the hyperlinked images from the IDB). So far participants from more than 80 developing countries have attended the College in ICTP, Trieste. They have triggered tens of Medical Physics activities and courses in their countries using the materials from the College [12]. This way hundreds of colleagues from developing (and other) countries have received help in the practical implementation of the profession. The ICTP College will be described in another chapter.

Beginning in 2004 Prof. Perry Sprawls developed a comprehensive tele-teaching process using a combination of methods, including web-based visuals and Skype, to teach from one country to another. It was the first extensive use of tele-teaching in the profession. One of the first MSc Medical Physics programmes using this to offer e-learning plus tele-teaching was at the University of Malaya, an activity led by Kwan H Ng and supported by the Sprawls Foundation. This was before the development of commercial teleconferencing (tele-teaching) programs that have expanded this form of education.

2.3 Various Directions of e-Learning after 2000

After 2000 e-learning entered in most professions. A useful book was published in 2003 by Springer "The Internet for Radiology Practice", A Mehta (ISBN 0-387-95172-5). The book promoted Teleradiology and included an extensive list of web sites with e-learning materials related to radiology, but also useful for medical physics.

Around the end of 2002 another set of CDs with teaching materials appeared – issued by the International Atomic Energy Agency (IAEA). As EMERALD, these three CDs (focussed on Radiation Protection) were covering 3 main fields of Medical Physics – Diagnostic Radiology, Nuclear Medicine and Radiotherapy. They included ready lecturing materials as Power Point slides. These 3 CDs were also distributed free and were of great help to the medical physics community. Some of their slides included images from the EMERALD Image Database. The easy inclusion of images to the digital teaching materials was now almost a standard for medical physics. These excellent materials also included Manual for Trainers and Multiple Choice Questions [1,13,14].

The increased use of e-learning in Medical Physics led to the invitation from the Editorial Board, led by R Allen, of the Journal of Medical Engineering and Physics in 2004 to run a special issue on e-learning. The Special Issue on e-Learning in *Medical Engineering and Physics* was published in 2005 (vol. 27, No.7, September 2005, Guest Editor S Tabakov). It soon triggered significant interest and some of its papers were among the most frequent downloads of the Journal. This high professional interest in e-learning was very promising for the profession. This way in 2008 another Journal - *Biomedical Imaging and Intervention* published its Special Issue on e-Learning (Guest Editor Kwan Ng).

e-Learning was gaining popularity in Medical Physics and Engineering and a number of new projects and activities were initiated. This was only natural as, apart from the specific professional knowledge, our colleagues had excellent computer and software skills. These projects could be grouped in three main directions of e-learning development:

a. Development of e-learning modules

These were projects such as EMERALD, EMIT and Sprawls.org, other examples of such courses were the project *Demystifying Biomedical Signals* (a signal-processing educational project led by University of Southampton, R Allen, A De Stefano, D Simpson, M Lutman) [15] and *A web-based course on Medical Physics for School Teachers* (led by University of Lund, B-A Jonsson) [16], etc. Such e-learning modules continue to be developed and to be welcome by colleagues – for example the *i.TREATSAFELY* tool of Pawlicki et al [17]; *the Personal Dosimetry module* of Koutalonis et al [18], etc.

A common feature of such projects is that they are very informative (with many images and diagrams) and are easy to update. However these modules required inventiveness in the development and organisation of teaching materials. One important element for such modules was the added facility to print the material on paper – i.e. these are excellent for hybrid/blended learning (classical and e-learning). Usually such modules have long life (depending on the use of software tools).

A variation of this trend is the Virtual Library of the American Association of Physicists in Medicine (AAPM), launched around 2006. This is an excellent educational tool, based on the videos of many open lectures presented at the AAPM meetings [19]. The web site is with free access for medical physicists from the developing countries (http://www.aapm.org/education/VL). This library is now open for free to all colleagues from LMI countries.

Specific e-learning module on Radiation Protection was developed during 2010. This was due to the fact that developing a common international Radiation Protection training was quite difficult due to the significant difference between the respective legislation in various countries (around 2010 this was harmonised in the European Union and such programmes were developed with the active involvement of ESR and EFOMP) [20, 21]. The first such project*MEDRAPET*(Medical Radiation Protection Education and Training) was coordinated by J Damilakis. The project will be described in a separate chapter, together with other EU projects with EFOMP involvement. The 2015 CRC book (IOMP&IRPA-commissioned) *Radiation Protection in Medical Imaging and Radiation Oncology* (Editors R Vetter and M Stoeva) also discusses issues related to the international approach to Medical Radiation Protection education/training.

b. Development of e-learning Computer simulations

These are projects simulating the functions of medical equipment. Some very useful simulations were developed in University of Patras, Greece (for medical image processing, including X-ray equipment simulator, a project led by N Pallikarakis) [22], University of Cagliari, Italy (an X-ray equipment simulator, a project led by V Fanti) [23], etc. Such e-learning simulations continue to be developed– for example the Radiotherapy simulators of Hartmann et al [24] and Kirby et al [25]; the simulation of Linear Accelerator of Carlone et al [26], etc.

The common feature for such projects is that they are very effective teaching tools, but are difficult to develop. Most importantly - they are software dependent and usually have short life cycle (some of the simulations above stopped working after several years). Some other simulations (e.g. in the field of Radiotherapy, as the project Prism, led by B Hartmann and J Meyer, used in University of Canterbury, New Zealand) have prolonged life, but still the use of specific software makes their practical implementation more difficult (especially in developing countries) [24].

Very useful teaching resources are interactive GIF images. Although not a simulation, these provide an easy way to understand complex processes. An example of such resources is the collection of the Colorado University [27]. This web site included also software link helping the users to create their own interactive GIF images. Others also promoted various software tools [28], although a number of commercial tools already existed.

In fact Computer simulations in Medical Physics existed from the beginning of the 1990s. For example an Image Backprojection Reconstruction simulation on a floppy disk was prepared by a colleague from India and distributed through the IAEA. The 1990 decade, and the first decade of the 2000, saw a number of very good simulations in the field of Imaging and Radiotherapy. However this trend lost speed during the second decade of the 2000, as a number of simulations stopped working with the introduction of new 64-bit PC Operating systems, which discouraged some teams.

AAPM is most active of medical physics societies in keeping the profession informed about various online simulations, modules and other resources [29,30] (the Education activities of AAPM will be included as a separate chapter of the History project). Similarly IOMP opened a new online Journal (Medical Physics International) oriented toward education/training and professional issues, including e-Learning (to be described further down).

c. Development of Course-management systems

Development of tailor-made Course-management systems is the most difficult one and rarely used. Such a programme was developed in the Medical Physics Centre in Plovdiv, Bulgaria by M Stoeva and A Cvetkov [31], but was difficult to maintain. Most educational programmes these days use one of the standard Course-management e-learning platforms (Virtual Learning Environment, VLE, or LMS – Learning Management System) - e.g. Moodle, Web CT, Blackboard, etc. These are in fact programmes managing the delivery of the material and the teaching process. These platforms facilitate the process of learning by allowing easy access to lecture notes, as well as providing the management of the educational programmes. Examples of such use of these e-learning platforms in MSc programmes can be seen at [32,33,34].

A very useful educational web site was launched in September 2006 - the IAEA Radiation Protection for Patients (RPOP) web site (rpop.iaea.org) – a very big project led by the IAEA (initially coordinated by M Rehani) [35]. This project was a combination of modular, structured programme and information hub (Fig. 13).

This free website is orientated towards a very large audience – medical physicists, radiologists, radiographers and various medical staff applying radiation, but most importantly - patients. The web site provides free download of training materials as Power Point slides and posters on radiation protection. This was one of the first professional web sites to allow download of large files with Power Point presentations and other materials. Soon the web site was at the top of the "Radiation Protection" lists of all Search engines. This was helpful for many patients undergoing radiation procedures in medicine and currently this is the most visited web site in the profession with hundreds of thousands visits per year (c. 286,000 in 2012).

This large web site is supported by a team in IAEA and has regular updates. Most of the materials are translated into Spanish and Russian. This web site is also used as a portal to various Radiation Protection IAEA projects – e.g. SAFRON (an integrated voluntary reporting registry of radiation oncology incidents and near misses). The significant contribution of IAEA for the education, training and e-learning in medical physics will be described in a separate chapter.

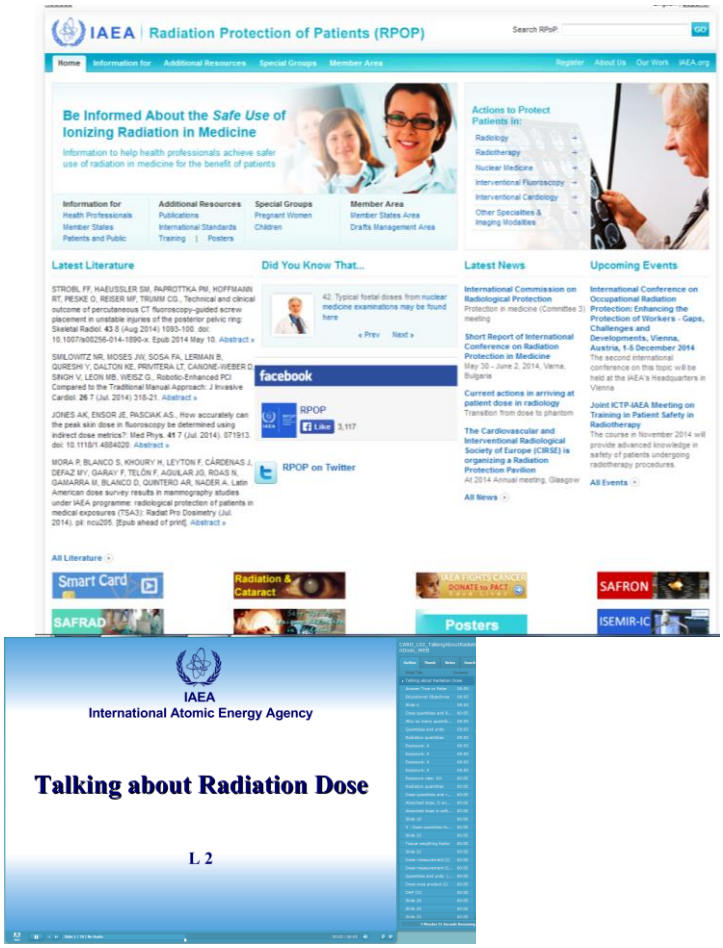

Fig. 13 The Home page of the IAEA RPOP Web site and first slide of one of the Power Point presentations (from 2015).

2.4 Medical Physics International Journal

The interest in education and training, and the need of a stable forum to discuss the e-learning development led to the launch of an IOMP Journal on the subject "Medical Physics International" (MPI). The new ISSN 2306-4609 for it was obtained at the end of 2012 and the first issue produced in April 2013, as a free on-line Journal (published twice a year). Its web domain was registered as www.mpijournal.org [36] . The Co-Editors in Chief were approved as P Sprawls and S Tabakov and the first Editorial Board included also: KY Cheung, M Rehani, W Hendee, T Suk Suh, V Tsapaki, S Kodlulovich Renha, A Krisanachinda, T Ige, M Stoeva, A Cvetkov, J Damilakis, R Wu, V Tabakova. Since its beginning the MPI Journal gained steady popularity, having at the beginning c. 4000 visits per month. As per the official server statistics, during 2018 the visits to the MPI Journal during March 2018 are c.11,100 (about 60% being from LMI countries). A number of e-learning and other educational and professional projects were published in the MPI Journal. This will be further described in other chapters.

The large number of on-line resources in medical physics require the development of a catalogue of these e-learning materials, which to be regularly updated and available to all colleagues. The free online IOMP Journal "Medical Physics International" is well suited to host and update such a catalogue.

3. Medical Physics e-Encyclopaedia and Multilingual e-Dictionary of Terms

The quick international dissemination of the e-learning materials (in English) of projects EMERALD and EMIT led to the need of a Multilingual Dictionary of Medical Physics [37]. The first Thesaurus of this Dictionary was made as part of project EMIT, supported by all EMIT Consortium members (listed in the respective paragraph).

3.1 Medical Physics e-Dictionary of Terms

The development of the Dictionary followed original methodology described in the free e-book "The Pioneering of e-Learning". In brief - an Identification number (ID) was assigned to each term from the Thesaurus and all translations were based on the IDs of the English terms. The ID number was the main identificator of each term. These were arranged in a Master Table (in MS Excel), where the rows with IDs were fixed. New columns however could be added to the Master table – a column for each language. The first column of the Master table was the ID, and the second column – the English language terms (arranged alphabetically, according to the Thesaurus compiled by the Consortium) – these two columns were also fixed. All additional columns were added by the translation groups – one per language (Fig. 14) .

Groups of translators were formed in each language, usually including specialists in the main fields of the professions (Physics of: X-ray Diagnostic Radiology, Nuclear Medicine, Radiotherapy, Ultrasound Imaging, Magnetic Resonance Imaging, Radiation Safety). General terms were covered by all translators (mainly terms related to relevant frequently-used terminology from physics, mathematics, medicine, etc). Each Language Group received the Master Table and inserted their translated terms in their dedicated Language-column (one term in a cell, as per the ID).

	A	B	C	D	E	F
1	ID	English (master file) Final update	BULGARIAN	Lithuanian	CHINESE correct	Arabic
11	10	3D (three dimensional)	тримерен (3D)	3D (trimatis)	三维	ثلاثي الابعاد
12	11	3D display	тримерен дисплей	3D vaizduoklis	三维显示	عرض ثلاثي الابعاد
13	12	3D imaging	тримерно изобразяване	3D vaizdavimas	三维成像	تصويرثلاثي الابعاد
14	13	3D spatial abilities	възможност за тримерно изобразяване	3D erdvinė geba	三维空间能力	قدرات (امكانات)فضائية ثلاثية الابعاد
15	14	3D visualization	тримерна визуализация	trimatis (3D) vaizdinimas	三维可视化	تصور ثلاثي الابعاد
16	15	Helium	Хелий (He)	Helis	氦	هيليوم
17	16	A number	атомен номер	Numeris, skaičius	A 模式	العدد الذري A
18	17	A mode	А режим (в ехографията)	A-moda, būdas, režimas	原子序数	نمط (طريقة) A
19	18	Abdominal imaging	изобразяване на абдомена	Pilvo (abdominalinės) srities vaizdinimas	腹部成像	تصويربطني (جوفي)
20	19	Absolute risk	абсолютен риск	Absoliuti rizika	绝对风险	مخاطرة (مجازفة) مطلقة
21	20	Absolute scale of merit test	абсолютна скала (за изпитване) на качеството	Absoliutinės kokybės vertinimo skalės testas	绝对标准刻度测试	المقياس المطلق لاختبار الاستحقاق
22	21	Absorbed dose	погълнатата доза (доза)	Sugertoji dozė	吸收剂量	الجرعة الممتصة

Fig. 14 Dictionary Master Table with translations, showing also colour coded queries during the Terms translations

Each Translation Group had its own Language Coordinator, who was responsible for collecting and verifying the translations from the Group members (usually colleagues with different specialisms). The Language Coordinators were in contact with the Main Dictionary Coordinator (the EMIT Coordinator, later EMITEL Coordinator), where all important partial results were sent, and where the Master Table was kept (with all languages). Translations in need of further discussion were highlighted in colour. If a specific term did not exist in a certain language, the English term was included in the corresponding cell in the Language column.

During the process of this development the Thesaurus was gradually updated with new terms coming from the specialists involved in the project. This was mainly due to the quick evolution of the profession in the past decade and the related inclusion of new terms. To handle this, the IDs of the existing terms were left 'as is', and a new continuation of the main English Master Table was made (again in alphabetical order). The additions to the Thesaurus were made in three stages, each new inclusion of a batch of terms starting after the next round number (in 500 increments) – i.e. ID 4000, ID 4500, etc (e.g the second batch is from 4001 to 4320; after time the third batch is from 4501 to 4817; the next one would start with ID 5001, etc). A total of 756 new terms were added this way after ID 4000.

The first e-Dictionary was developed early in 2003 (using Visual Basic) and was engraved on a Mini CD, together with demos of the e-learning materials EMERALD and EMIT. The software developers for this CD-Dictionary were A. Cvetkov and M Stoeva (AM Studio). The Mini CD included an executive file of the Dictionary and required its installation on the PC of the user. The interface required selection of the two languages for the translation (From .. To…) and included the necessary fonts. This user-friendly design allowed very easy use of the Dictionary (Fig. 15). There were three Dictionary windows: the Left Search window (From), where the user types the term; the Left Display window, which presents a limited list of the respective Language table from the database (from the Input Language); a Right (To) window presenting the translation of the selected text from the Output language.

Close to two thousands of these Mini CDs with the first in the profession Multilingual e-Dictionary were distributed free during the World Congress on Medical Physics and Biomedical Engineering in Sydney, Australia (August 2003). This dissemination of the Dictionary and the Thesaurus of Medical Physics Terms triggered the development of some future Dictionaries in specific languages (transferred later into EMITEL).

The inclusion of new languages in the Dictionary presented new challenges because of the different alphabets,

which were difficult to be handled by the existing software used for the mini CD. However at that time the current web technologies advanced enough to allow transferring the Dictionary on the Internet. A new domain was registered and a new web-design was created by A. Cvetkov and M Stoeva from AM Studio (www.emitdictionary.co.uk). The design was using directly the synchronised tables of the Dictionary.

This new phase of the e-Dictionary (the Web Dictionary) was dependent on the settings of the Internet browser, which allowed various alphabets to be used. This led to rapid expansion of the number of languages in the Web Dictionary. However at that time the search was still based on the beginning of the first word of the term. This was not convenient for complex terms (e.g. the term Dose did not call related complex terms starting with other letter – as Absorbed dose or Effective dose). This was later improved in the final EMITEL Web Dictionary.

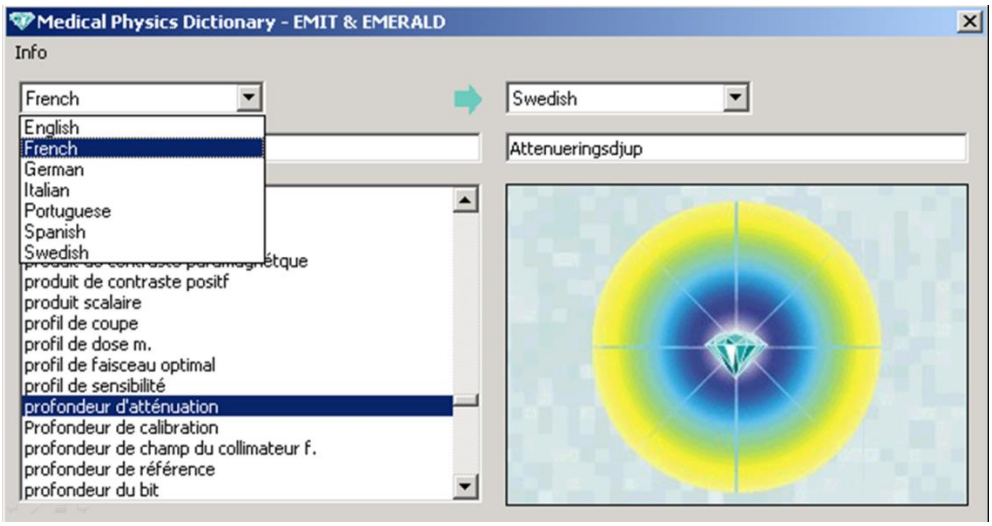

Fig. 15 Graphic interface of the first CD-based Medical Physics Dictionary (2003-2005) distributed free on mini CD, and also with the EMERALD and EMIT CDs

The Web Dictionary design included again a user-friendly interface with Windows for Input and Output Languages and a small Search window for the term to be translated. The results were displayed as two parallel tables of corresponding terms (scrollable).The new Web Dictionary was launched in 2005 and for several months attracted thousands of users (it is still in use at www.emitdictionary.co.uk, in parallel with the e-Dictionary web-version included as part of the e-Encyclopaedia web site).

The Dictionary of terms with explanations was further developed in the project EMITEL, which aimed at developing explanatory articles for each term, thus transforming it to an Encyclopaedia. This project was approved for funding by the EC during 2006 and will be described further in this chapter.

A new web site was developed for EMITEL (www.emitel2.eu, opened for free use in 2009), handling both the Dictionary and the Encyclopaedia. The new web-design was introduced again by A. Cvetkov and M Stoeva from AM Studio, which then became full partners to the project. It included a new Web database, but still used the initial parallel language tables, which proved very useful. Two Search Engines were designed – one of those being Multilingual (handling the Dictionary), the other one – in English, only for the Encyclopaedic entries [38].

The EMITEL Dictionary Search engine allowed direct search for terms, or part of terms. Hence a search for the term Dose is now returning all complex terms including Dose - Absorbed dose, Effective dose, Mean absorbed dose to air, etc. This also reduced eventual problems with misspelling.

Currently the Dictionary exists in 29 languages (in 8 alphabets), translated by colleagues listed at the end of this chapter. Thus the original 7 languages were supplemented by new 22 languages and the final Dictionary included: Arabic, Bengal, Bulgarian, Chinese, Croatian, Czech, English, Estonian, Finnish, French, German, Greek, Hungarian, Italian, Japanese, Korean, Latvian, Lithuanian, Malaysian, Persian, Polish, Portuguese, Romanian, Russian, Slovenian, Spanish, Swedish, Thai and Turkish. Most recently a new language is being

prepared for inclusion (in Georgian language), the translation being coordinated by G Archuadze. Currently the Dictionary and the Encyclopaedia EMITEL are updated with new terms (a new project to be completed in 2020). Thousands of colleagues use these e-learning materials each month.

3.2 Medical Physicse-Encyclopaedia

The Medical Physics Thesaurus and Dictionary were used for the development of the firste-Encyclopaedia of Medical Physics. This was realised by the project EMITEL (2006-2009), which included also the IOMP and concluded as a huge project including about 300 specialists from 36 countries.

The project EMITEL (acronym of European Medical Imaging Technology e-Encyclopaedia for Lifelong Learning) was prepared with objectives: to develop an original e-learning tool, to be used for lifelong/continuing learning of a wide range of specialists in Medical Physics and Medical Imaging Technology. The tool was planned to be linked to the existing EMERALD and EMIT materials and to include (additionally to Medical Imaging) Radiation Protection&Hospital Safety and Radiotherapy topics, thus forming a one-stop knowledge database (or rather a Web portal) for colleagues who want to acquire a specific competence, as well as for those who want to refresh their knowledge and to keep up with the new developments in medical physics.

The project Consortium included as partners: King's College London - School of Medicine and Dentistry; King's Healthcare Trust; University of Lund; Lund University Hospital; University of Florence; AM Studio, Plovdiv, Bulgaria; the International Organization for Medical Physics (IOMP). Project Manager and Coordinator was S Tabakov. The results of the project were also aimed at increasing the academic information supporting the e-learning tasks, developed by EMERALD and EMIT.

One specific feature of this project was that it required parallel work of 7 Work Groups. The Groups were organised as per the internal topical division of the profession:

-Diagnostic Radiology (X-ray) physics
-Magnetic Resonance Imaging physics
-Nuclear Medicine physics
-Radiotherapy physics
-Radiation Protection in Medicine
-Ultrasound Imaging physics
-General topics

EMITEL was a very large project – not only the largest in the profession, but also with extremely complex coordination. Finally, EMITEL with its pre-project and post-project phases took about 5 years, plus another year for paper-print preparation.

The Encyclopaedia contains a large number of entries (articles) – one per each term in the Thesaurus. The size of the entries varies, most of these being between 150 and 500 words). Special Guide was made for all project contributors. The Encyclopaedia was written in English, what required additional work from the UK team to edit some of the entries coming from the international teams.The development of the Encyclopaedia followed original methodology described in the free e-book "The Pioneering of e-Learning in Medical Physics" [1].

The Refereeing of the Encyclopaedia was going in parallel with the writing of articles, to fit with the limited project time. After the refereeing the entries were also used by MSc students from King's College London, who commented on the clarity of explanations of terms. A system of specific file organisation was developed at the Coordination office, allowing to specify the phase of development of each entry and its readiness to be released (Fig. 16). A master Database was also developed at the Coordination office to allow monitoring the overall progress of the project.

A special web portal for the Encyclopaedia was developed by the project partners M Stoeva and A Cvetkov from AM Studio – www.emitel2.eu [38, 39]. It includes 3 parts:

-a web Database containing all Encyclopaedic entries, as well as the Dictionary and its translations
-a Content Management System (CMS) with various levels of access, which was used for the update of the database and control of the parts of data to be visualized;
-a web site for access to the information (www.emitel2.eu), which has two search engines – one multilingual for the Dictionary and one in English to perform search inside the text of the entries.

Each Encyclopaedic entry file went through several stages of Development/Refereeing/Editing:
-Internal refereeing (in the Workgroup)
-First Editing by the author, based on remarks from Internal refereeing
-Sending to project Coordinator for upload to the web site for internal viewing only: preview.emitel2.eu
-Feedback from the other Workgroups
-Possible Second Editing by the author in case of need
-Sending the file to an External Referee by the project Coordinator
-Feedback from External Referee discussed by the author and the Workgroup
-Final (Third) Editing by the author
-Final sending to project Coordinator for upload to the web site (www.emitel2.eu - open for all)

From the beginning it was agreed that the Encyclopaediawould consist of a large number of small articles, thus allowing easier search. The academic level of the Encyclopaedia entries (articles)was agreed to be at Master level (MSc, or equivalent) and above. This way it was not necessary to use very simple explanations, and at the same time was a way of allowing medical physics MSc students to use EMITEL as an educational resource [40].

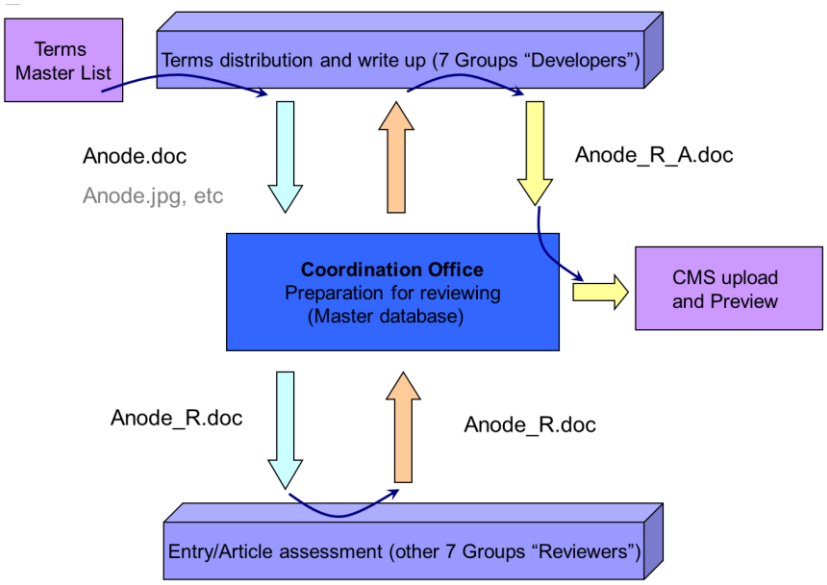

Fig. 16 EMITEL project main workflow (example of an entry "Anode" with its files and changing of file names during the process of Preparation > Refereeing/Reviewing > CMS Upload). This was performed in parallel in all 7 Groups of Developers and Reviewers. The distribution was at the Coordination office with 4 parallel large folders of the Encyclopaedia (depending on Entry the development stage) – Initial Entry; Reviewed Entry; Approved Entry; Upload

There were three main types of Encyclopaedic articles/entries – short, medium and large (the latter going to about 500 words). Specific Guides were made for the different types of articles/entries. The use of font sizes, images, tables, diagrams, captions, References, etc was standardised in order to help the significant number of authors to prepare entries with unified look.

The web site handling both the Encyclopaedia and the Dictionary provided all necessary links between them. The interface allowed both - to use separately the two elements and to use these simultaneously. To serve both functions two separate Search Engines were added to the Web site. The first Search Engine serves the Multilingual Dictionary (it can work with various alphabets, as per the Internet browser settings of the user). The second Search Engine serves the Encyclopaedic articles (entries in English), this way allowing search for synonyms, acronyms and other words inside the text of the articles. This Search Engine can also search within articles specific to one of the areas of the Encyclopaedia (X-ray Diagnostic Radiology, Nuclear Medicine; Radiotherapy, Ultrasound Imaging, MR Imaging; Radiation Protection). Each entry displayed at the web site has an additional Area indicator (e.g. the entry Anode is available in two areas/fields – General and Diagnostic Radiology) (Fig.17). Selecting the area field displays the relevant Entry. The web site was developed with a special "hidden" part – Content Management System, which allows updates of the material online.

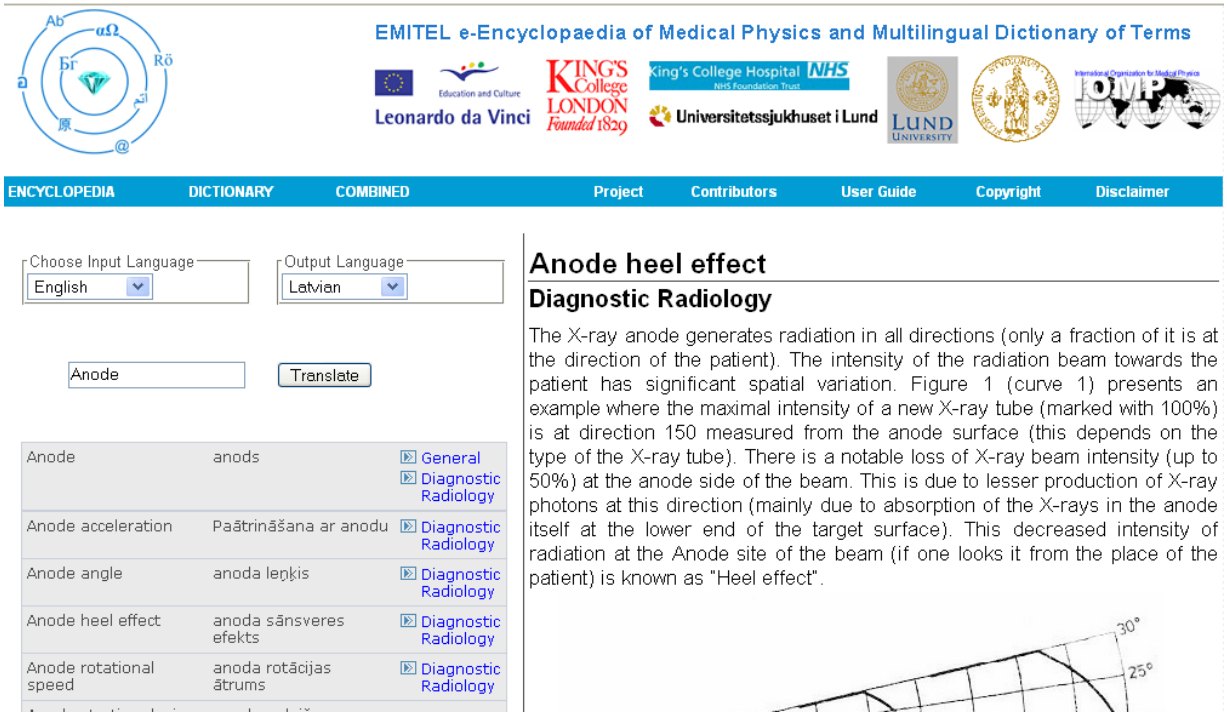

Fig. 17 Sample Print-screen of the Encyclopaedia web site – Combined Dictionary and Encyclopaedia

The large assessment conference (EMITEL Conference) was held at the premises of our long-standing project partner - ICTP, Trieste (23-26 October 2008) – Fig.18. Its main objective was the assessment of the e-Encyclopaedia materials, their further development, dissemination and use. The Conference included project members, also a group of students, who used the e-Encyclopaedia for several months and gathered very useful feedback, and also medical engineering professionals, thus widening the scope of EMITEL. The Conference was by invitation only, gathering about 70 specialists - leading experts in Medical Physics. These included 21 present and past Presidents of Medical Physics Societies, Federations and Organisations (including a number of IOMP Officers). All assessors (and later all users) found the Encyclopaedia a very useful e-learning resource

The number of articles on the e-Encyclopaedia web site is about 3200. Their volume (Word files and JPG images) is more than 1GB. The images, diagrams, etc are approx. 2500. The final printed volume, in alphabetically arranged A4 pages, depends on the typeset - when the default Times New Roman 12 was used, it reached 2100 pages.The e-Encyclopaedia EMITEL was launched at the World Congress WC2009 in Munich and from the very beginning until this day it has a steady flow of about 50,000 searches per month. The Encyclopaedia of Medical Physics was also printed on paper by CRC Press [41].

The further paper-pint of the Encyclopaedia by CRC Press reduced the number of pages. Currently the Encyclopaedia is being updated – a project to be completed by 2020 (and print as Second Edition by CRC Press). EMITEL e-Encyclopaedia of Medical Physics and its Multilingual Dictionary of Terms has thousands of users from around the world. For information – the web server official statistic for 3 months (from January to March 2018) shows total visits 30,775 (c.10,000 in Europe; c.13,000 in Asia; c.4,000 in North America; c. 2,000 in South America; c.2,000 in Africa).

Fig. 18 EMITEL Conference, ICTP, Trieste, Italy, 2008 (part of participants): from L>R front row sitting: E Morris, E Chaloner, J Calvert, G Clarke, J Chick, A Krisanachinda, I-L Lamm, M Radwanska, B Allen, M Lewis, R McLauchlan, I Horakova, M Almqvist, V Tabakova, S Tabakov, A Benini; front row standing: C Oates, K Olsen, G Mawko, M Petersson, B-A Jonsson, R Magjarevic, M Secca, E Moser, J Boyle, P Bregant, N Pallikarakis, S Christofides, D Bradley, F Schlindwein, S Keevil, R Wirestam, F Milano, E Podgorsak, D Frey, A Cvetkov, K Keppler, D Goss; second row standing: M DeDenaro, C Deehan, M Buchgeister, G Taylor, A Simmons, T Schaeffter, J Thurston, D Platten, H Terrio, M Leach, T Jansson, C Deane, P Zarand, A Evans, M Grattan, P Smith, C Lewis

4. Conclusion

The projects and results described in the chapter about e-Learning in Medical Physics showed the dedication of many medical physicists to e-learning, as well as their innovative thinking. The profession has now truly embraced e-learning, this being now an intrinsic part of its education and training. Obviously this will continue and further new e-learning materials, simulations and other innovations will enhance the global professional development of medical physics.

The double growth of medical physicists during the decade 1995-2005 (compared with the previous 3 decades) coincides with the introduction of e-learning in the profession. Further the double growth of the medical physicists globally in the following decade 2005-2015, coincides with the extensive use of e-learning (Fig.19). This data show that e-learning, as part of the overall emphasis on education and training in the profession, is an important element of the global growth of the profession [42].

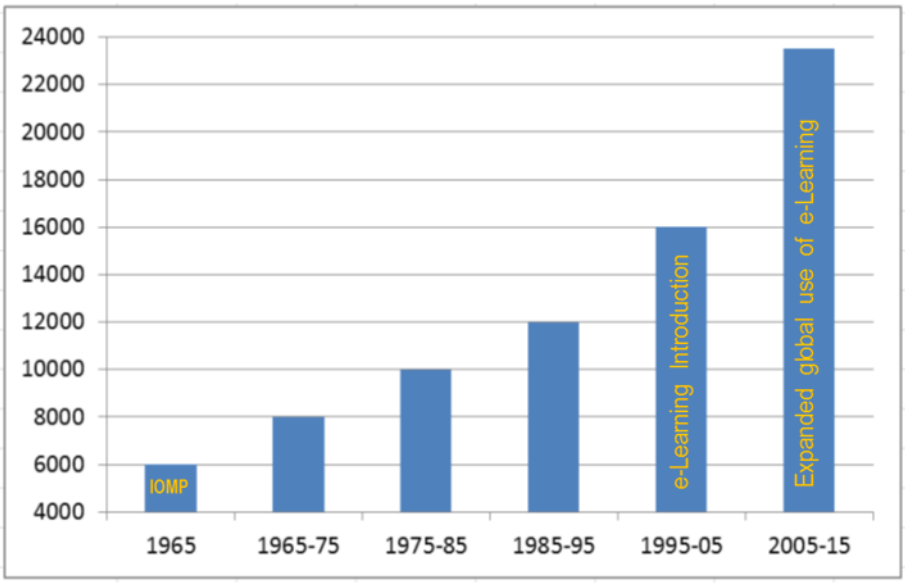

Fig. 19 Global growth of medical physicists in the world in the period 1965-2015

Most of the pioneering projects, which laid the foundation of e-learning in medical physics were developed on voluntary basis by hundreds of colleagues from many countries. The main players of this process were mentioned in the text of the chapter. Here below we list also all contributors to the extremely large projects on the Multilingual e-Dictionary of Terms and the e-Encyclopaedia of Medical Physics.

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