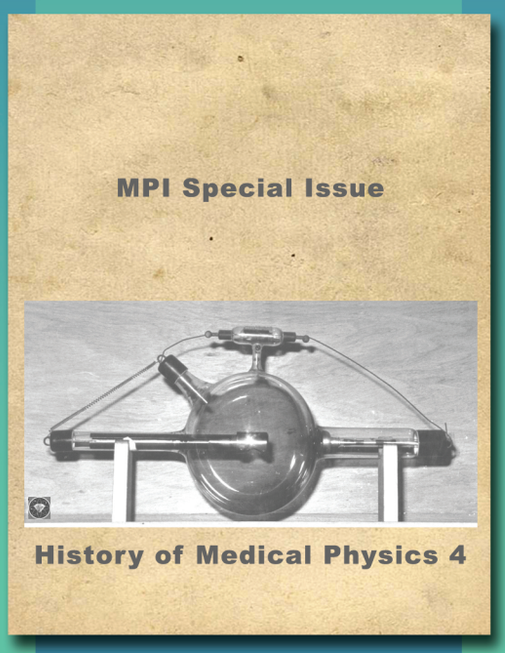
MEDICAL PHYSICS
International



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The Journal of the International Organization for Medical Physics

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EDITORIAL

Slavik Tabakov, Perry Sprawls and Geoffrey Ibbott

MPI Special Issues Co-Editors

The contributions of modern medical physics to high quality healthcare for society are possible because of the highly advanced technology and clinical methods for both diagnostic and therapeutic clinical procedures that have developed over the years. The evolution of these technologies and methods is the result of extensive discoveries, inventions, and developments by many physicists, engineers, and other professionals each making specific contributions. That is our history and heritage. Knowledge of that continuing process provides context for modern medical physics clinical activities and appreciation for the foundation of our profession. Providing open access to that for all medical physicists and students around the world is the objective of the IOMP History Project and publications in Medical Physics International.

Our team continues to work on the Medical Physics International (MPI) issues despite the difficult pandemic situation around all of us. We are grateful to all colleagues who contribute to the wide spectrum of the Journal and its Special issues. During the past two months the MPI 2020 regular issue and the Special Issue No.3 attracted significant interest with about 15,000 visits to the web site www.mpijournal.org (c.5200 from North America; c.4800 from Asia and Oceania; c.3800 from Europe; c.700 from Africa; c. 400 from South America). We are glad that the open access to this IOMP publication triggers such interest in the profession and supports many colleagues worldwide.

The Content of the MPI Special History Issues and the interest to these underline the objective of the History project: to research, organize, preserve, and publish on the evolution and developments of medical physics and clinical applications that are the foundation of our profession. The history articles can be accessed at : http://www.mpijournal.org/history.aspx

In this MPI Special Edition No.4 we provide four articles from the IOMP History Project, which again present a mixture of methods and equipment history and of professional development in medical physics regions and sub-regions.

The paper on History of Cobalt 60 Radiation Therapy is authored by J. Van Dyk, J. J. Battista, and P.R. Almond – well known specialists in the field. It is significant that the authors have been personally involved in this progress and also share important memories of this foundation part of our professional history. The paper includes comprehensive list with references, tracing the most important steps of this development.

The paper on History of Computed Tomography (part I) traces the initiation of the method up to Spiral CT – a step-by-step process of developments and innovations increasing the quality and capabilities of CT as a medical procedure. The paper includes biographical notes of the main scientists involved in the CT invention and introduction. The paper is prepared by P Sprawls, who is one of the pioneers in the implementation of CT.

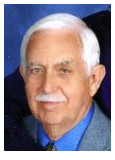
The paper on History of Professional Development in the South-East Asian region is related to the 20th anniversary of SEAFOMP. It continues the MPI Issue of May 2020, with focus on the medical physics development in this part of the world. The paper is prepared by the SEAFOMP colleagues, who played significant role in this development (and were collaborating Editors of the previous MPI issue).

The paper on History of Education and Training Conferences and Courses in Central/Eastern Europe is related to the 40th anniversary of EFOMP. It presents the first important steps of the profession in this part of the world and the education and training projects developed there, later used also in other countries. The paper is prepared by S Tabakov, who spent over 25 years on the initiation and organization of Conferences and projects in Central/Eastern Europe.

A number of these papers were planned to be presented at the AAPM Annual Conference History Symposium, but due to the current situation this will be postponed for the next year.

We welcome the contribution of colleagues from all societies, organizations and companies, who plan to join the History project in its various volumes. We look forward to your contributions to the Project.


Prof. Slavik Tabakov


Prof. Perry Sprawls


Prof. Geoffrey Ibbott

A RETROSPECTIVE OF COBALT-60 RADIATION THERAPY: *"THE ATOM BOMB THAT SAVES LIVES"*

J. Van Dyk[1], J. J. Battista[1], and P.R. Almond[2]

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Abstract — **The first cancer patients irradiated with cobalt-60 gamma rays using external beam radiotherapy occurred in 1951. The development of cobalt-60 machines represented a momentous breakthrough providing improved tumour control and reduced complications, along with much lower skin reactions, at a relatively low cost. This article provides a review of the historic context in which the advances in radiation therapy with megavoltage gamma rays occurred and describes some of the physics and engineering details of the associated developments as well as some of the key locations and people involved in these events. It is estimated that over 50 million patients have benefited from cobalt-60 teletherapy. While the early growth in the use of cobalt-60 was remarkable, linear accelerators (linacs) provided strong competition such that in the mid-1980s, the number of linacs superseded the number of cobalt machines. In the meantime, other technological advances on linear accelerators provided increased capabilities such as intensity modulation and image guidance, developments which were *not* implemented on cobalt-60 machines until decades later. The simplicity and relatively low cost of cobalt teletherapy provided an incentive for its use in lower-income situations where financial resources are constrained and cancers are often more advanced, generally requiring simpler treatment techniques. Cobalt-60 sources continue to be used in a variety of other treatment contexts including high-dose-rate brachytherapy and stereotactic radiosurgery. However, radiation safety and security concerns with the possibility of malicious applications has developed a mentality of removing these sources from usage as much as possible. Furthermore, with the increased demand for cobalt-59 in other contexts, the future supply of cobalt metal will be strained. The combined concerns of greater complexity and potentially reduced reliability for cobalt-60 machines with add-on devices, and the security concerns for cobalt-60 radioactive sources have significantly reduced the early advantages of cobalt-60 over linacs and, thus, has resulted in a significant decline in their use.**

Keywords — **cobalt-60, radiotherapy, history, teletherapy, brachytherapy.**

CONTENTS


Sylvia Fedoruk push-buttons Saskatchewan's potent cobalt-bomb machine into position to treat a cancer patient.

Physicist Dr. Harold Johns, born in China, designed the anti-cancer bomb, and heads Saskatchewan's pioneer unit. "We asked for it and we got it," he now says proudly.

The Atom Bomb That Saves Lives

Canadian scientists have turned the deadly atom into a dynamic healer. Three hundred times more powerful than radium and six thousand times cheaper, radioactive cobalt looks like our best bet yet in the war against cancer. And only Canada is equipped to produce it

By ERIC HUTTON

Figure 1. Opening page of an article written by Eric Hutton for MacLean's magazine, Canada's premier current affairs magazine. The picture on the left is the cobalt-60 machine designed by Harold Johns who is shown on the right. The medical physicist operating the machine is Sylvia Fedoruk who eventually became the lieutenant governor (the Queen's representative) for the Province of Saskatchewan, Canada (1988-1994) [66].

I. INTRODUCTION

The headline and the opening sentences of an article in MacLean's magazine, Canada's premier current affairs publication, written by Eric Hutton and published on 15 February 1952 read: **"The Atom Bomb That Saves Lives"** "Canadian scientists have turned the deadly atom into a dynamic healer. Three hundred times more powerful than radium and six thousand times cheaper, radioactive cobalt looks like our best bet yet in the war against cancer. And only Canada is equipped to produce it." (Figure 1) [66]. It was clear that cobalt-60 radiation therapy was considered the new breakthrough and game-changer for treatment of cancer patients and it was considered international news. In this review, we will provide the historical development of cobalt-60 radiation therapy, placing it into a context with other relevant developments and provide a sense of the global impact on improvements in cancer treatment. Major references for this historical development include: a detailed paper by Robison [109] who provided an excellent overview of the quest for the development of megavoltage beams, both x-ray and gamma ray; four articles published in 1999 in the newsletter of the Canadian Organization of Medical Physicists, *InterActions* [33-35;96]; a book and editorial by Peter Almond outlining the history of development of the first cobalt-60 unit in the United States [3;4]; a handbook from London, Ontario on early experience and guidance for cobalt-60 teletherapy [118]; an encyclopedia contribution by J.R. Cunningham [36], a couple of history articles [63;115], in addition to the many other references cited in this paper.

II. BRIEF HISTORY OF RADIATION THERAPY

X-rays were discovered in 1895 by Wilhelm Conrad Röntgen and this was followed shortly thereafter with the discovery of radioactivity by Antoine Henri Becquerel in 1896. Already in 1896, consideration was given to the use of radiation for medical purposes [109]. In 1898, Becquerel along with Pierre Curie and Maria Sklodowska-Curie were able to separate two radioactive isotopes from uranium: polonium and radium. It was very shortly after these discoveries that both x-rays and radioactive isotopes were used to treat a variety of cancers, initially primarily for dermatological conditions. With Coolidge's introduction of "deep therapy" tubes of 200 kV in 1922, the subsequent period until the 1940s used mostly low energy x-rays (perhaps up to 400 kV but generally in the range of 50-250 kV) and radium and radon for the treatment of cancer patients. Radon sources were used for interstitial treatments and radium was used for both external beam radiotherapy as well as brachytherapy. High voltage generators were also developed by Van de Graaff and Trump and attained megavoltage levels (1-2 MV). The first megavoltage x-ray cancer treatment took place in Boston on 1 March 1937 [115]. A 1.2 MV generator was later installed at Massachusetts General Hospital in 1939 and operated until 1955. These were colossal electrical devices with limited dose rates and were intimidating for cancer patients. It is historically interesting that John D. Trump, uncle of present-day United States President Donald Trump, collaborated with R.J. Van de Graaff at the Massachusetts Institute of Technology (MIT) on megavoltage electrostatic x-ray generators; 43 generators were in use clinically until 1969 [115]. Their research also addressed synchronous field shaping [123;139], which is discussed more later in the context of cobalt-60 teletherapy.

III. LIMITATIONS OF RADIATION THERAPY UNTIL THE 1950s

The limitations of x-rays included high skin doses and a lack of deep penetration as would be needed for tumours deep inside the body. Furthermore, the dose rates were such that the x-rays needed to be applied with fairly short treatment distances, which resulted in shallower depth of dose penetration. The outputs of x-ray tubes and generators were quite variable resulting in complications in their dose calibration [109].

The problem with the alternative radiation source, radium, was that it was difficult to produce in high enough activities for external beam therapy; as part of its nuclear decay process, it emitted a radioactive gas resulting in radiation safety concerns; and it was prohibitively expensive (about $885 per mgm in 2020 US dollars!) [109]. A typical therapy radium unit required a radium pack in the range of 5 to 10 grams affordable only in well-endowed hospital or research institutions with the equivalent of million-dollar budgets (2020 currency). Treatment machines needed to operate at short treatment distances to maintain high enough dose rates and to keep patient treatment times reasonable. A typical dose rate was still only ~3 cGy per minute at a depth of 10 cm in tissue. Finally, these units had poor source shielding resulting in radiation exposures to the staff. Although low-activity cobalt-60 sources in the range of 100 Ci were considered as replacement for radium in tele-radium treatment units, the optimal use of cobalt-60 required much higher activity and completely redesigned equipment as described in Section VII.

IV. RADIOACTIVE SOURCE DEVELOPMENT

The discovery of the stable form of cobalt, i.e., cobalt-59, occurred circa 1735 and is attributed to the Swedish chemist Georg Brandt (1694–1768). Cobalt metal is found in the earth's crust generally in a chemically combined form and is often produced as a by-product of copper and nickel mining. The word *cobalt* is derived from the German *kobalt*, from *kobold* meaning "goblin", a

superstitious term used for the ore of cobalt by miners. Cobalt-based blue pigments (cobalt blue) have been used since ancient times for jewelry and paints, and to impart a distinctive blue tint to glass [135]. Currently, the Democratic Republic of the Congo produces about 63% of the world's cobalt with an expectation that this will rise to 73% by 2025. The next top three producers of cobalt are Russia, Australia and Canada. Raw cobalt metal is relatively inexpensive. Prices peaked in 2018 at almost US$100.00 per kg but currently trade at $30.00 per kg. The demand for cobalt is expected to rise with the increased production of electric cars as cobalt continues to be used in their lithium-ion batteries.

It was prior to and during the Second World War in the 1930s and 40s that nuclear reactor developments were at an embryonic phase with the resulting discovery that when uranium was bombarded with neutrons, it broke into separate fragments, with a process known as nuclear "fission". This paved the way for producing "artificial" radioactive isotopes with potential biomedical applications.

An early report, perhaps the first, concerning cobalt-induced radioactivity was published by Rotblat in *Nature* in 1935 [111], although the estimated decay scheme and half-life was far from as we know them today. Sampson et al in 1936 from Princeton University were the first to observe a long-lived isotope of cobalt-60 by *irradiating cobalt-59 with neutrons* and reported a half-life to be more than one year [113]. Inconsistent results on the gamma energy spectrum and half-life persisted in experimental results reported by Risser [3;108] and Livingood et al. from University of California, Berkeley [88;89;135]. The half-life riddle was finally resolved by Nelson et al in 1937 [3;108].

In England in 1937, Arthur Eve (formally of McGill University, Canada) and Leonard George Grimmett reported on therapeutic medical applications of artificial radioactive sources *versus* x-rays [46]. Grimmett was a visionary medical physicist with prior clinical experience in the United Kingdom with radium devices. A detailed biography and record of his achievements can be found in the book "Cobalt Blues" by Peter Almond [4]. Starting in 1929, Grimmett worked at the Westminster Hospital in London, England. During World War II, Grimmett became convinced that cobalt-60 would be an exquisite replacement for radium in a practical radiotherapy machine [3;25], a proposal that was punctuated by J.S. Mitchell [95]. Starting in 1948, Grimmett played a key role in the design of an early cobalt therapy unit to be installed at the M.D. Anderson Hospital in Houston, Texas, as will be described later. He collaborated with Marshall Brucer, research chairman of the Oak Ridge Institute for Nuclear Studies (ORINS) and Dale Trout of the General Electric X-ray Corporation (Milwaukee, Wisconsin). He published the first article describing a cobalt therapy machine design in 1950 in a local journal [3;57], preceding a key paper by Harold Elford Johns et al of Canada [71] (Figure 2).

The activation of cobalt-60 is represented by the following nuclear reaction:

$$^{59}_{27}\mathrm{Co} + {}^{1}_{0}n \rightarrow {}^{60}_{27}\mathrm{Co} \qquad (1)$$

The nuclear cross-section reflective of the probability of capturing a slow neutron in cobalt-59 is large (i.e., 37 barns) so that sources of high specific activity could be produced in a nuclear reactor in reasonable time. The neutron flux in the Canadian NRC NRX reactor described later was considered intense for that era, ~10^{13} neutrons per cm^2 per second. The first cobalt-60 sources reached a net activity of ~1,000 Ci with an exposure time of approximately 1.5 years [71].

The decay of cobalt-60 which then yields the megavoltage gamma rays is denoted by:

$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + {}^{0}_{-1}e + \bar{\upsilon}_e + 2\gamma(1.17\ \&\ 1.33\ \mathrm{MeV}) \qquad (2)$$

where $^{0}_{-1}e$ represents a beta particle with a maximum energy of 0.32 MeV and $\bar{\upsilon}_e$ is an antineutrino. The half-life of this decay process is 5.27 years and, as indicated, two megavoltage photons are emitted with energies of 1.17 and 1.33 MeV. Hence, cobalt-60 yields an ample supply of quasi-monoenergetic megavoltage photon radiation [71].

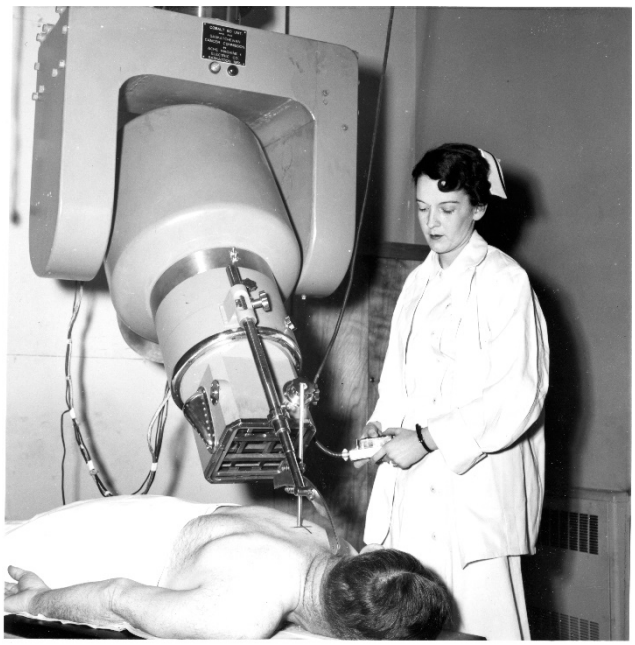

Figure 2. The Saskatoon Unit designed by Harold Johns and students, and John MacKay of Acme Machine and Electric of Saskatoon. From University of Saskatchewan, University Archives and Special Collections, University Photograph Collection, A-2244.

Assuming a typical source size of 6 cm^3 weighing ~55 grams, the yield from the NRX reactor was ~20 Ci of cobalt-60 per gram of original *cobalt-59* metal assumed to be of high purity. As Professor Harold Johns [74] might have stated "It is left to the student to show that the fraction of NRX-activated cobalt-60 was only ~2% of initial cobalt-59". If this exposure had been prolonged (impractically) to several *decades*, this fraction would have equilibrated at ~8%, yielding of ~100 Ci per gm of *cobalt-59*. If it were possible to increase the reactor neutron flux significantly by a factor of 10 (i.e., 10^{14} neutrons per cm^2 per s) to outpace the source decay, the theoretical limit is the specific activity (1,100 Ci per gram of cobalt-60*)*. It cannot be reached practically because of limited exposure time, and self-attenuation and scatter within the source capsule. However, sources of ~500 Ci per gm of cobalt-59 are routinely produced today for current manufacturers of cobalt medical devices [36].

Important events in the development of nuclear reactors that preceded the clinical implementation of cobalt therapy machines are now described. Enrico Fermi helped build the first nuclear reactor in Chicago in 1942 as part of the Manhattan project. He noted that neutrons travelling at slower speeds were more effective at splitting nuclei compared to faster ones. Hence, they developed "moderators" to slow the neutrons. While the United States used graphite as a moderator, the team in Montreal, Canada, working under Canada's National Research Council (NRC), used heavy water, D_2O [87]. The uranium used for these reactors was mined and processed by Eldorado Mining and Refining Ltd. The Canadians built a research reactor in an outpost known as Chalk River, approximately 190 km (120 miles) northwest of Ottawa, the nation's capital. The first small heavy water reactor was the Zero Energy Experimental Pile (ZEEP) and on 5 September 1945 the first successful, peaceful atomic reaction occurred outside of the United States, just one month after the atomic bomb explosions in Hiroshima and Nagasaki. The subsequent "big brother" to the ZEEP reactor also located in Chalk River was to be known as the National Research Experimental (NRX) and first went critical in 1947. The reactor emerged from the World War II alliance of Canada, Britain, and the United States [4]. It also used natural uranium and heavy water to provide a significant neutron flux capable of producing a variety of radioactive isotopes including cobalt-60. The heat generated by the reactions was cooled by water drawn from the adjacent Ottawa River [87]. *The neutron flux at that time was ten times greater than any other known reactor in existence*, thus allowing for faster production of isotopes along with higher specific activities and placing Canada at the forefront of nuclear reactor and efficient isotope production for medical research and applications. This was *the* enabling technology for the development of clinical cobalt-60 teletherapy machines for the world.

During this same time period, Harold Elford Johns, a physicist, who was then with the Saskatchewan Cancer Commission, recommended the procurement of a betatron (22 MeV) and also the *de novo* development of a cobalt-60 teletherapy unit. His original cost estimate for constructing a new cobalt unit was between $2,500 and $7,000 in 1950 dollars or $25,000-$70,000 in today's dollars [63]. He found enthusiastic financial support for *both* devices from the Premier of the government of Saskatchewan, T. C. ("Tommy") Douglas. Douglas is recognized for establishing Canada's socialized national medical care program, in addition to being the grandfather of actor Kiefer Sutherland.

In the autumn of 1949, Chalk River scientists A.J. Cipriani and W.B. Lewis began the activation of enough cobalt material to prepare three radioactive teletherapy sources in the NRX reactor, each with a goal of one kilocurie. Johns assembled his physics research team in Saskatoon, Saskatchewan and with clinical colleague, Dr. A.T. ("Sandy") Watson, submitted a request to the NRX staff for a cobalt-60 teletherapy source on 13 August 1949. The second source request came from Donald Green and Roy Errington of Eldorado Mining and Refining Limited for integration into a commercial unit destined to Dr. Ivan Smith. The installation was planned for the Ontario Institute of Radiotherapy, then located in the War Memorial Children's Hospital across the street (South Street) from the former Victoria Hospital in London, Canada. The first two cobalt sources were made from thin wafers, 0.052 cm thick and 2.55 cm in diameter (i.e., the size of a Canadian 25-cent coin). Once removed, they were to be stacked to an overall thickness of 1.3 cm and sealed in a metal cylindrical capsule to produce the final teletherapy source. The requisition for the third source was ambiguous. It was originally requested by physicist W.V. Mayneord and reserved for the Royal (now Marsden) Hospital in England [87]. However, export restrictions forced a cancellation of that order. The third source production was then re-assigned to satisfy a custom order received from Gilbert Fletcher and Leonard Grimmett of the M.D. Anderson Hospital in Houston, Texas, working in collaboration with the Oak Ridge Institute of Nuclear Studies (ORINS) and General Electric X-ray Corporation (Milwaukee, WI). This source was designed differently by Grimmett as a stack of four plaques, each 2 x 2 x 0.25 cm^3. These plaques were initially exposed in the Oak Ridge reactor, but it would have taken over five years to achieve the desired total activity of 1,250 Ci. The plaques were therefore eventually transferred to the "hotter" NRX reactor, but net activity after a 10-month exposure was still disappointing (650 Ci) due to excessive self-attenuation. A secondary "top-up" irradiation in the reactor was applied for six months, and the sources were not ready until summer of 1952, with a final activity of 876 Ci. There was additional misfortune for the M.D. Anderson group with Grimmett's

untimely death due to cardiac arrest in May of 1951 [3]. He did not live to see his dream of a cobalt machine materialize in the United States and beyond. Cross-border regulatory issues, dosimetry studies at the Oakridge Institute for Nuclear Studies (OINS), and bunker construction delays resulted in final clinical installation of the General Electric unit at the M.D. Anderson Hospital in September 1953. Meanwhile another machine was installed in Los Angeles, leading to the first case treated in the United States (23 April 1952). That unit remained in service until 1962.

V. THE RACE TO FIRST CANCER TREATMENTS

In 1947, Mayneord and A. Cipriani, a Canadian biophysicist, measured the absorption characteristics of cobalt-60 gamma rays and determined that the incident radiation consisted of two spectral lines at 1.1 and 1.3 MeV [92]. Mayneord had also delivered a series of lectures in a two-week course on the physics of radiotherapy at Toronto General Hospital in 1946 at which time he also spoke enthusiastically about the possibility of cobalt-60 as a source of radiation for a teletherapy unit. In the audience was Harold E. Johns who was visiting from the University of Saskatchewan. As a point of historical financial interest, Dr. Johns' salary at that time was reported to be $3,600 per annum, or $54,000 in today's dollars, evenly split between the two collaborating institutions [63]. The profession of medical physicist was at its infancy and its societal value was not yet fully recognized. Cobalt-60 developments played a large role in changing this perception. The Mayneord lectures piqued Harold Johns' interest in cobalt-60 teletherapy. The combination of a stronger, spectrally simpler, smaller and cheaper radioactive source in comparison to radium provided multiple reasons to make it a tremendous substitute for radium and megavoltage x-ray generators.

As a positive side effect of the Mayneord lectures and associated notes, Harold Johns went on to write the first edition of *The Physics of Radiation Therapy* which eventually evolved to four editions with subsequent editions being entitled *The Physics of Radiology* and published with co-author John Robert (Jack) Cunningham [73;74;130]. This became the classic textbook for medical physicists in training around the world for many decades.

As noted previously, Grimmett was a creative visionary physicist who was known for having designed and built an innovative 5-10 gram teleradium unit in which the source was pneumatically moved into the unit. When Grimmett moved to Houston in early 1949, he and Gilbert Fletcher planned to purchase one of the units, without the radium, and load it with a 50 Ci cobalt-60 source. When on a visit to Oak Ridge in August 1949, Grimmett was told that a 1000 Ci source was possible, he knew that an extended treatment distance, compared to the teleradium unit was possible and he immediately started to design a brand new unit to take full advantage of such a large amount of activity. From a radiation safety viewpoint, he also realized that such source in a radium unit would present a radiation hazard.

In February 1950, the isotope division of the Atomic Energy Commission (A.E.C.) and Oak Ridge called a meeting in Washington D.C. to discuss and solicit designs for a cobalt-60 irradiator. Thirty-three people attended from around the U.S. and Canada made up of radiologists, physicists, governmental agency representatives and industry. It was at this meeting that the U.S. became fully aware of the extent of the Canadian program and that contrary to earlier promises, the Oak Ridge reactor would not be able to deliver on a 1000 Ci source. Grimmett immediately started to make arrangements to get the cobalt-60 sources for his unit transferred to the Canadian reactor to be activated [49].

It was at this meeting that Grimmett and Johns met for the first and only time and there is no record that they corresponded afterwards. Both were extremely busy with research and development duties and Grimmett unfortunately passed away 15 months later [4] – this being an era well before the availability of e-mail! However, the two groups continued to be in contact. In July 1951, Brucer and Kerman, the radiologist, from the Oak Ridge project visited Canada to follow up on the status of the cobalt sources and took the opportunity to visit with Johns and the radiation oncologist, Sandy Watson, in Saskatoon. In addition, Watson and Fletcher, who were good friends, were constantly in contact.

Roy Errington had been hired by Eldorado Mining and Refining Limited in 1944 to setup a sales department to sell uranium. He also became aware of Mayneord's theoretical proposal and its strong commercial potential, with a favourable half-life, ideal for recurrent sales as a supply item. When Eldorado Mining won the right to sell cobalt-60, Errington decided to develop equipment to help sell his new product [87]. On his way to a meeting in Chicago in 1949, Errington met with Dr. Ivan Smith in London, Ontario, Canada and was assured that cancer therapists (now called radiation oncologists) would actually use a teletherapy cobalt-60 machine. It is not clear if this meeting was pre-planned or simply serendipitous, but it most certainly was appropriate. London had become the second largest cancer centre in the province of Ontario. Smith was a surgeon-pathologist and Chair of the Department of Therapeutic Radiology at the University of Western Ontario. Radiation oncology was not an established specialty in Canada at that time. His positive reaction to a clinical cobalt unit led Errington to seek internal corporate funding that accelerated

commercial development for such a machine.

A prototype commercial unit was designed by Donald T. Green of Eldorado Mining and Refining Limited and built under contract by the Canadian Vickers company of Montreal, Canada. With improvements in manufacturing, production of the first commercial units (Eldorado A, a product name resonating with an eye-catching Cadillac vehicle) transferred back to Eldorado Mining. The ***Eldorado A*** **became the first cobalt-60 teletherapy unit in the world to be used clinically on a cancer patient on 27 October 1951 in London, Ontario, Canada** (Figure 3). This first unit was purchased with a special grant from the Ontario Cancer Treatment and Research Foundation (OCTRF) for the Ontario Institute of Radiotherapy of Victoria Hospital in London, Ontario, Canada, with a special price tag of $25,000 dollars in 1951, equivalent to $250,000 today. The first *rotational* unit, called the Theratron Model B, was designed in 1952 and sold at a price that was double the Eldorado A. This was the beginning of the Theratron series of cobalt units sold by Commercial Products Division (CPD) of Atomic Energy of Canada Limited (AECL) [5], which eventually became MDS-Nordion, and, now, is Best Theratronics.

In parallel with these developments, Harold Johns led an independent research group in Western Canada at Saskatoon. His machine design (Figures 2 and 4) was later adopted by the Picker X-ray Company and featured a Johns-McKay collimator to produce variable field sizes without the use of individual lead cones (see Figure 13). The collimators (known as Johns-McKay collimators) were built under contract by the Acme Machine and Electric Company in Saskatoon [77]. The first treatment in Western Canada occurred on 8 November 1951 – just a few weeks after the world's first treatment in London, Ontario. The Saskatoon patient was a 43-year-old woman with a cervical tumour, treated at Saskatoon's University Hospital (now Royal University Hospital). She lived to be over 90 years of age! This led the Saskatoon group to claim bragging rights for the first *successful* cobalt patient treatment. To be fair, it is not known how many curative cases were treated in London between 27 October and 8 November 1951. Saskatoon's cobalt machine treated 6,728 patients until it was replaced in 1972. Meanwhile, Dr. Johns left Saskatoon in 1962 to become the Head of Physics at the Princess Margaret Hospital (PMH) and Ontario Cancer Institute (OCI) in Toronto. Anecdotally, it was reported in the recent Hollywood movie, *First Man*, that Neil Armstrong attempted to consult with Dr. Johns regarding the possible cobalt-60 treatment for his very young daughter who had developed a brain tumour. Dr. Johns continued his creative work with innovations in radiation chemistry, ultraviolet damage to DNA, and medical imaging (CT). As an aside, two authors of this article (JVD, JJB) worked in the same institution with Dr. Johns for many years in Toronto and have benefited immensely from his exceptional attention to computational and experimental details in medical radiation physics research.

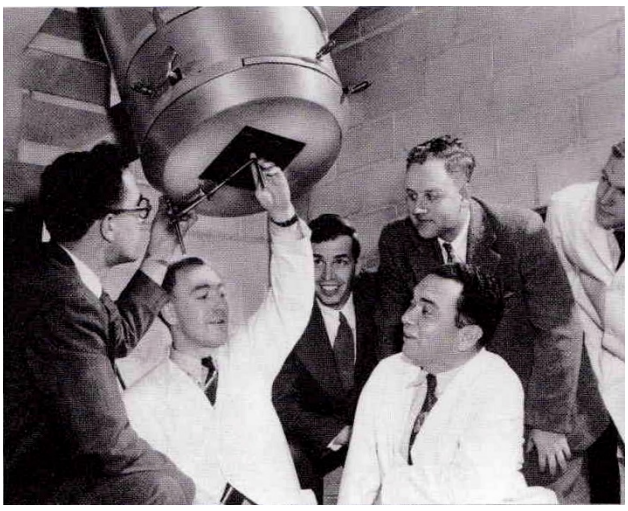

Figure 3. The Eldorado A at Victoria Hospital in London Ontario in 1951. The first patient treatment was given on 27 October 1951. Don Green (far left) was an engineering physicist involved in its design. Roy Errington (second from right) became the founder of MDS Nordion and heavily involved in the initial development and sales of cobalt teletherapy. Dr. Ivan Smith (right foreground) was a surgeon-pathologist and Head of the London cancer clinic. Dr. Frank Bately (with arm up below the Eldorado unit) was the radiation oncologist. From [87].

The close timing of the initial treatments led to the designation that London and Saskatoon were engaged in a "race" to achieve the world's first cobalt-60 irradiation of a cancer patient; it clearly became a photo finish considering all the interim delivery logistics and source calibration issues for a novel source. London's source had undergone extensive radiation measurements, including the first depth-dose curves, at Canada's National Research Council in Ottawa [43;44]. In effect, the Eldorado A arrived in London *pre-calibrated* in 'plug-and-play' configuration on 23 October 1951. This neutralizes unfair

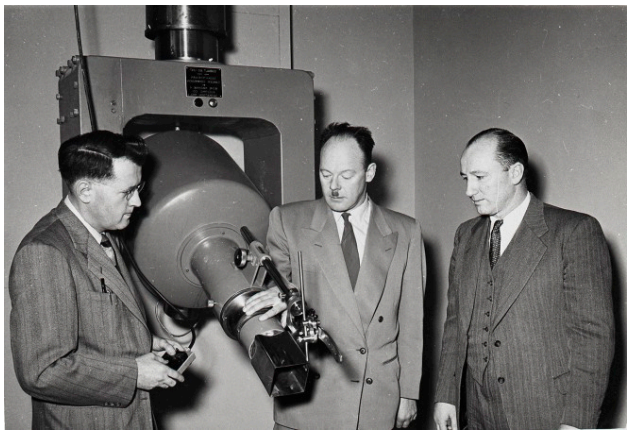

Figure 4. Saskatchewan cobalt unit with initial lead plug collimator system. From left to right: Dr. Harold Johns, John MacKay and Dr. T.A. Watson admiring their handiwork. Reproduced with permission from [63].

criticism that clinical commissioning of the London therapy unit had been "skimpy". The dosimetry was rechecked locally by Dr. J.C.F MacDonald who was urgently recruited to replace Jack Brown who had contracted tuberculosis while traveling in the United Kingdom to investigate British medical physics practice. At that time, the United Kingdom was considered the epicenter for training of medical doctors and physicists in the field of radiation oncology. The world's first treatment of a cancer patient indeed proceeded quickly on 27 October 1951 under Dr. Ivan Smith's leadership. This first patient was treated for palliation with a very poor prognosis and only lived a limited time. An interesting video summarizing some of this history can be found on the Saskatchewan's Western Development Museum website [134].

The unit destined for the M.D. Anderson Hospital was built by the General Electric X-ray Corporation of Milwaukee and ready to be displayed at a meeting of the American Roentgen Ray Society in 1951. For a variety of technical and military reasons due to the Korean war, and the premature death of Grimmett, the first treatment at the M.D. Anderson Hospital, Houston, Texas, was delayed until 22 February 1954 (Figure 5). After the Washington meeting in February 1959, the M. D. Anderson Group realized they were never in the running to deliver the world's first cobalt teletherapy treatment. In fact, the first patient treatment with a cobalt-60 unit in the United States occurred on 23 April 1952 at the Los Angeles Tumor Institute. The US unit was designed by Russell Hunter Neil with a source consisting of six stacks containing 18 pieces constituting 108 individual micro-sources. The six stacks were arranged in a single cylinder, 4.33 cm high, 3.5 cm diameter for a total weight of cobalt of 181.74 gm and a total activity of 1080 Ci (February 1952). The machine output was 32 r/min at 70 cm from the source [4]. This late entry to the race does not belittle the leading contributions of all three pioneering groups (Saskatoon, London, Houston) who started this fast-paced competition to improve radiotherapy for the world.

A surge of similar technical developments also occurred in other countries including the Soviet Union, Japan, Denmark, Holland, and Sweden. By 1956, 218 machines were in operation in non-Russian countries and an estimated 160 were assumed in use in countries behind the "iron curtain" [23].

Table 1 summarizes key dates and times of the three locations in the race for cobalt-60 treatments and Table 2 compares timelines and the characteristics of the world's first two clinical cobalt-60 machines.

Evita Peron Story: On 21 May 1952, the Montreal Gazette newspaper published a story under the headline *Ontario Hospital Denies Evita Peron Treated There.* (Figure 6).

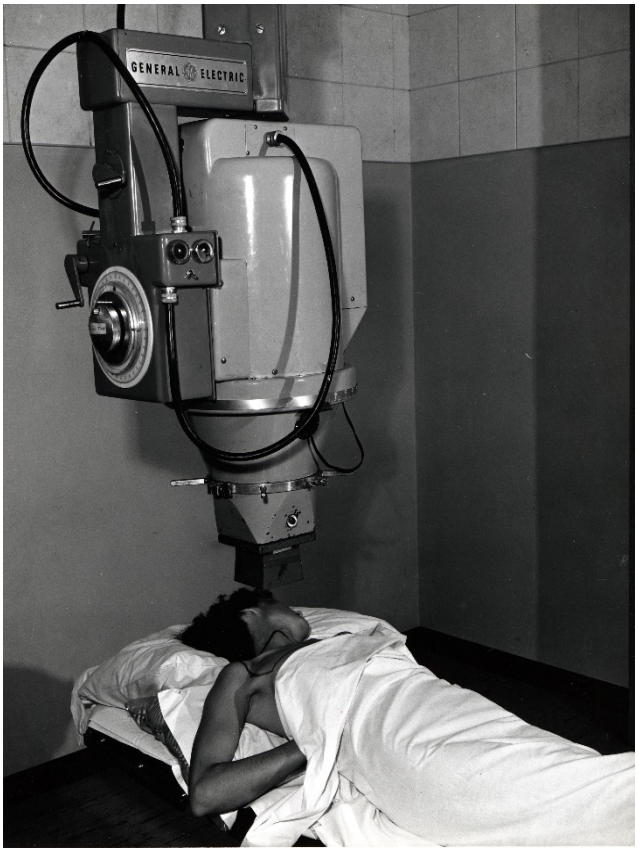

Figure 5. The Grimmett designed cobalt-60 unit marketed by General Electric and located at the MD Anderson Hospital in Houston, Texas. Image courtesy of the University of Texas MD Anderson Cancer Center Historical Resources Center.

Ontario Hospital Denies Evita Peron Treated There

London, Ont. May 20. —(CP)—The Toronto Telegram said today that Mrs. Juan Peron, wife of the Argentine dictator, underwent treatment with the cobalt bomb at Victoria Hospital here about three weeks ago. Officials at the hospital said they had no knowledge she had been there.

The report gave no hint of the ailment of the vivacious blonde first lady of Argentina. Radiation from the Canadian-developed cobalt bomb is generally a treatment for cancer.

The Telegram said Mrs. Peron was flown here under "the tightest of security cloaks."

Dr. Augustin Nores Martinez, the Argentine's ambassador to Canada, said in Ottawa that Mrs. Peron was in Buenos Aires all during the last month.

Dr Carman J. Kirk, Victoria Hospital superintendent, said he had no knowledge of Mrs Peron ever being admitted to the hospital, "even incognito" He said Dr. Ivan Smith, director of the cancer clinic, and Dr. Frank Batley, who directs treatment with the cobalt bomb, scoffed at the report. Dr. Batley denied that Mrs. Peron had received treatment at the clinic.

The politically-prominent Mrs. Peron, variously reported as 30 or 33, underwent a major operation in Buenos Aires last November. The one-time movie actress, known as Evita (little Eva) to millions of citizens of Argentina, had been ill several weeks with what doctors called acute anaemia. Indication that she had been suffering from cancer came when it was learned she had been treated by Dr. George T. Pack, a leading cancer specialist from New York.

A cobalt bomb similar to the one here is in operation at the University of Saskatchewan in Saskatoon. Doctors in Saskatoon said today Mrs Peron was not treated there.

Publication of the Toronto report brought to light the information that Argentina tried to buy the cobalt bomb before it was delivered to the clinic here. It is said to have offered up to $1,000,000 for the radioactive instrument produced in Canada for $50,000.

The bomb, powered by a core of cobalt made radioactive by being placed in Canada's atomic pile at Chalk River, Ont., produces radiation equal to that of $50,000,000 worth of radium.

Figure 6. A section from page 10 of The Gazette newspaper in Montreal.

To quote the opening sentences “The Toronto Telegram said today that Mrs Juan Peron, wife of the Argentine dictator, underwent treatment with the cobalt bomb at Victoria Hospital here (i.e., London, Ontario) about three weeks ago. Officials at the hospital said they had no knowledge she had been there.” During that time Dr. John C.F. MacDonald was a physicist at the London cancer centre and, as described earlier, had been involved in the original commissioning and dosimetry of the Eldorado A. (As a side note, in the early 1970s, Dr. MacDonald was also the graduate student supervisor of two of the authors (JVD, JJB) of this historical review.) As a follow-up to the Evita story, one of the authors (JVD), prior to a conference in Argentina, contacted Dr. MacDonald to obtain more background information. To quote from Dr. MacDonald’s e-mail of 9 May 2011, “Evita had ca uterus, and when the Argentines heard about the cobalt unit, they sent the Argentine ambassador to see Roy Errington (leader @ AECL) and to order one to be shipped to Buenos Aires immediately to save 'the poor shirtless ones of Argentina'. But Roy had to tell him that a source wouldn't be available for about a year. So, when AECL Commercial Products threw a big bash in London, the ambassador was invited, and the press took note. The next day, a Saturday, Frank Bately, the oncologist, and I were in the Clinic, and between us took innumerable calls from all over the world about Evita. - but that didn't stop the reports. She died soon after.” A further corroboration of this story can be found in a historic article in the Canadian Medical Association Journal [78]. Furthermore, one of the authors (JJB) was given access to archived files from Dr. Ivan Smith’s office in 1994 and was unable to find any clinical or communication documents whatsoever referring to Evita’s treatment. Case closed!

VI. COBALT TRUTHS AND CONSEQUENCES

The progression from kilovoltage to megavoltage energy was considered a giant leap forward in the practice of radiotherapy [126]. We previously noted some key physical advantages of cobalt-60 sources over radium and kilovoltage x-ray systems, such as cost-effectiveness, higher dose rates at a longer source-to-surface distance (SSD), and skin-sparing in the dose buildup region. The era of differentially targeting the tumour while limiting the radiation dose to surrounding tissue and organs at risk had arrived and there would be no turning back [105;107;123;139]. The following is an interesting quote from the British Medical Journal of 26 September 1959 (page 566), in the Section of Radiology on Supervoltage Radiotherapy, “Dr. IVAN H. SMITH (London, Ontario) reviewed the use of cobalt-60 in the treatment of oral cancer in the first 50 patients treated on a radical basis by means of the original 1-kilocurie Eldorado A unit. Five main conclusions could be drawn: (1) Tumour invasion of the mandible could be controlled. (2) Complete regression of disease recurring after previous treatment was possible.

Table 1. The teams in the race for cobalt-60 teletherapy.

	Saskatoon, Saskatchewan, Canada	London, Ontario, Canada	Houston, Texas, USA
Source delivered	30 July 1951	16 Oct 1951	July 1952
Unit Installed	17 Aug 1951	23 Oct 1951	Sept 1953
Calibration & commissioning	11 weeks	Pre-calibrated	
First patient treated	8 Nov 1951	27 Oct 1951	22 Feb 1954

Table 2. Canadian twins (adapted from [109])

	London, Ontario Unit	Saskatoon, Saskatchewan Unit
Manufacturing Company	Eldorado Mining and Refining Ltd	Acme Machine and Electric Co.
Hospital where unit is installed	Victoria Hospital	University Hospital
Lead Physician	Dr. Ivan H. Smith	T.A. “Sandy” Watson
Technical Design by	Donald Green Roy Errington	Harold E. Johns
Physics support	Radiology Lab and Physics Division of the National Research Council of Canada, Ottawa	Physics Department, University of Saskatchewan L.M. Bates, E.R. Epp, D.V. Cormack, S. Fedoruk
Machine support mechanism	Floor mounted	Ceiling mounted
Source shutter (On/Off mechanism)	Liquid mercury shutter	Motorized rotating wheel
Marketed by	Atomic Energy of Canada Ltd.	Picker X-ray Co.
Dedication date	11/12 Nov. 1951	23 Oct. 1951
Date of first patient treatment	27 Oct. 1951	8 Nov. 1951

(3) Nodes which were the site of metastases and which could be included within the treatment beam for the primary tumour could be controlled. (4) A very low incidence of bone necrosis was found. (5) There was no skin reaction, and mucosal reaction too was less. Occasionally high tumour-resistance was found. but of the 50 patients treated by the machine 19 had been free of tumour for periods ranging from 39 to 83 months. Further experience had been gained with the rotating hectocurie Theratron Junior using both rotation and wedge fields, either alone or in conjunction with fixed fields. In general, although the fixed field gave a somewhat better depth-dose with less integral dose and less penumbra, rotation offered an easier technique with no need for plaster fixation.”

The advantage of superimposing multiple overlapping fields emerged quickly, as illustrated in Figure 7. Gains in

clinical outcomes also soon appeared with the shift from kilovoltage to megavoltage energy [126]. Convincing evidence emerged from Princess Margaret Hospital in Toronto (now Princess Margaret Cancer Centre), rebutting some sceptics who felt that a novel treatment machine was just "an expensive toy for the physicists". Figure 8 shows the improved survival of cancer patients with cervical cancer in pre-war and post-war periods [26]. The main reason given for the clinical improvement was the availability of a higher energy beam (cobalt-60 versus 200-400 kV x-rays). Further improvements in survival with an even higher megavoltage energy from a 22 MeV betatron were reported; however, the gain was not only due to beam energy but also differences in patient setup, field size, absolute dose, and fractionation. The exact rationale for the improved survival was never ascertained [2] and later treatment techniques were modified away from the four-field oblique delivery. Megavoltage radiation became the new standard of clinical practice for a variety of tumour sites including cervix, Hodgkin's disease, head and neck, and prostate. The next significant leap forward came with the introduction of 3-D medical imaging introduced at a much later time (1970s). "Pixel-based" dose modelling based on x-ray computed tomography (CT) became the new norm, significantly improving the accuracy of dose distributions used in treatment planning decisions.

Table 3 provides a more detailed summary of the physical characteristics of cobalt and the corresponding impact on the design of a clinical therapy machine. The first kilocurie activity was made possible by the combination of an intense neutron flux in the NRX nuclear reactor and a generous nuclear capture cross-section of cobalt-59. Hotter, smaller, and cheaper sources, compared with radium sources, set the stage for *practical* megavoltage therapy of deep-seated tumours at reasonable dose rates. Extended SSD made cobalt therapy more comfortable for patients with greater clearance for patient setup, without an intimidating canon-like structure pointed closely at the skin. The early Saskatoon cobalt unit used a Lazy Susan rotating platform built into the floor to turn the patient while being exposed to a horizontal radiation beam. A similar treatment was achieved on the Eldorado A machine using a rotating chair (see Figure 9). Various forms of rotation therapy that have been considered are shown in Figure 10. The C-arm gantry of second-generation cobalt units allowed treatment with a horizontal patient setup – foreshadowing modern rotational techniques such as volumetric-modulated arc therapy (VMAT) and tomotherapy [27;41;91].

The beam penetration characteristics are the result of energetic gamma rays, enhanced by longer distance applications and laterally-scattered photons depending on field size. Percentage depth-dose values approached 60%

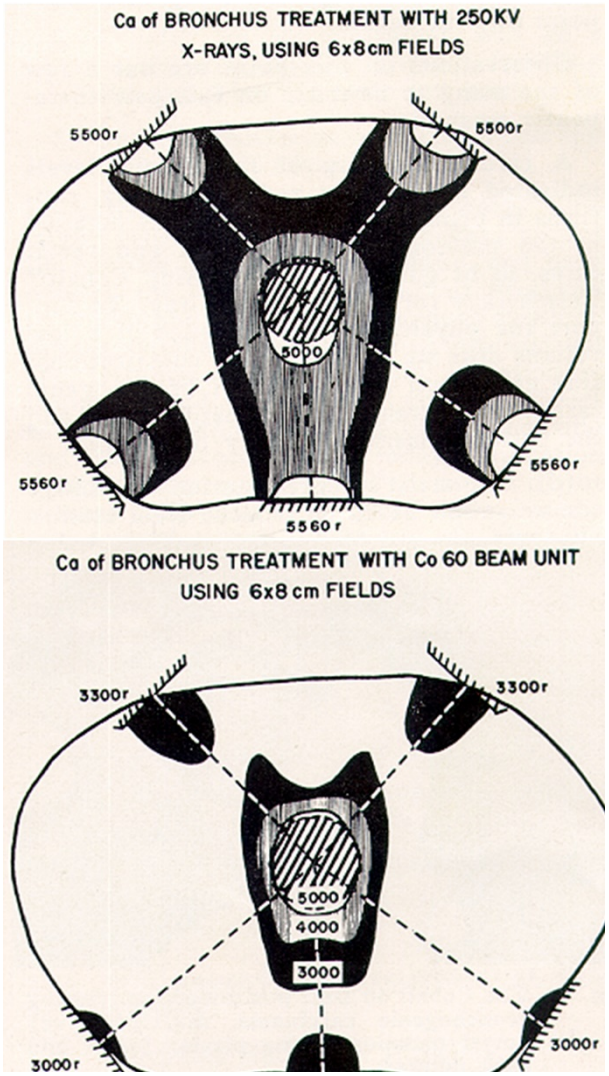

Figure 7 Comparison of dose distributions from 250 kV x-rays (top) and cobalt-60 (bottom).

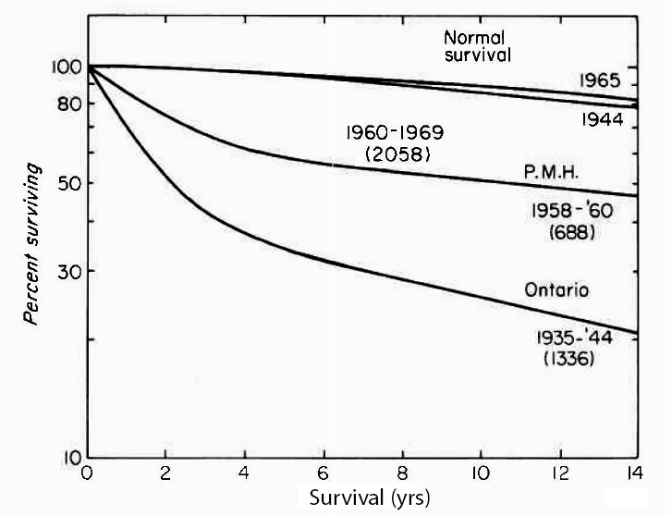

Figure 8. Survival curves for the kilovoltage and megavoltage for cancer of the cervix. With permission from [26].

Table 3. Major attributes of cobalt-60

Attribute	Numerical Values	Practical Consequence
Vivid blue colour	-	Used in glass, pottery, jewellery, ancient Egyptian murals
Cost of raw material Co-59	$250.00 per kg (1979) $30.00 per kg (2020)	Affordable and available (at present) Cost expected to rise for electric car battery technology
Nuclear Cross Section (neutron capture)	37 barns (x 10^{-24} cm^2) for cobalt-59	Induce radioactivity efficiently
Activity Yield from NRX neutron flux (10^{13} per cm^2 per s)	~20 Ci per g of Co-59 (1.5 year exposure)	Original source size (56 g)
Activity Yield from modern reactor flux (10^{14} per cm^2 per s)	~300 Ci per g of Co-59 (3 year exposure)	Higher dose rate, smaller sources Smaller geometric penumbra
Specific Activity (maximum)	1,100 Ci per g of Co-60	Theoretical limit for ultra-intense neutron flux
Exposure rate constant (Γ_x) Air KERMA rate constant (Γ)	1.29 R h^{-1} m^2 Ci^{-1} 307 µGy h^{-1} m^2 GBq^{-1}	Exposure (R) or Air KERMA (µGy) rate at 1 metre distance per unit activity (Ci or Bq)) Radiation protection vs distance
Source Activity (A) to achieve 256 cGy per minute at SAD = 100 cm (SAD = source-axis distance) RMM source specification (R per minute at 1 meter)	~13,000 Ci ~500 TBq RMM ≈ A (Ci) x Γ_x /60 (theoretical value)	Treatment duration for patient Patient throughput Higher activity enables longer SAD = 100 cm Improved depth-dose Open gantry – ease of patient setup and less stressful Rotational therapy High activity warrants extra security measures
Gamma Rays	1.17 and 1.33 MeV	Skin sparing (< 5mm) and bone-sparing Ease of calibration and dose distribution computation based on tissue electron density (per cm^3)
Half-Value Layer	11 mm Pb	Shielding Blocks/MLC beam shaping Radiation Protection – Room/Barriers
Half Life	5.26 years	Frequent dose rate updates (1% per month) Source replacement costs

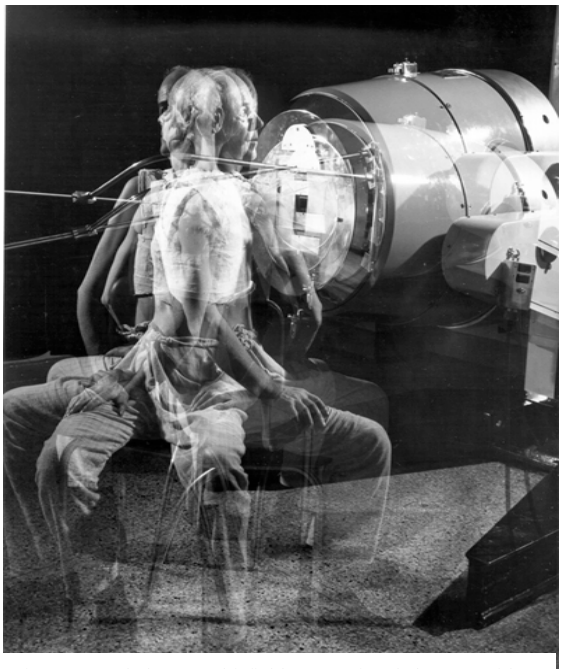

Figure 9. Cobalt-60 multi-field or rotational therapy with a rotating chair and the Eldorado-A. From the archives of the London Regional Cancer Program, London Ontario, held at the library of the University of Western Ontario.

at a depth of 10 cm, doubling the previous value for 'deep' x-ray beams (Figure 11).

Megavoltage photons liberate electrons in tissue with a finite range giving rise to the dose build-up (i.e., d_{max} = 5 mm) thereby achieving "skin-sparing". In addition, atomic interactions with all types of tissue, including bone, occur quasi-exclusively by the Compton scattering

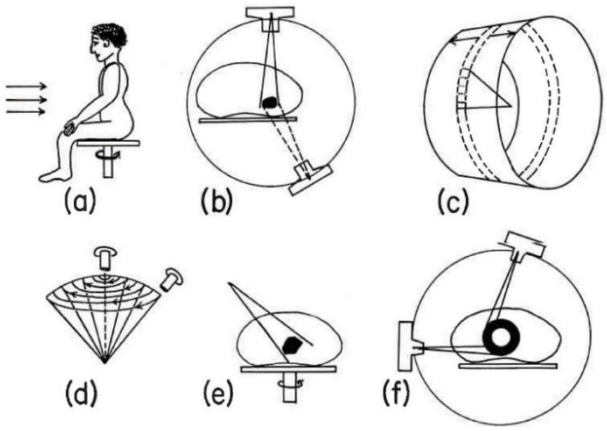

Figure 10. Schematic diagram illustrating the various forms of moving field therapy. From reference [73]. Courtesy of Charles C Thomas Publisher, Ltd., Springfield, Illinois

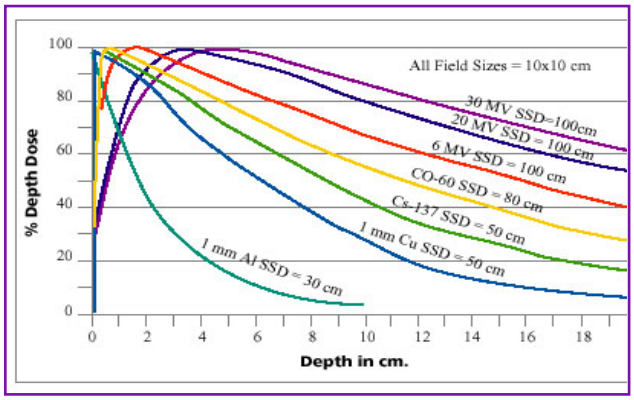

Figure 11. Percentage depth dose curves for kilovoltage and megavoltage beams for a field size of 10 cm x 10 cm.

effect *without* a photoelectric boost. This had a major clinical consequence, enabling dose escalation that had been previously limited by serious skin or bone reactions with kilovoltage x-rays. The close pairing of the two cobalt-60 gamma ray energies simplifies accurate dose calibration and computation of dose distributions, assuming a single effective energy of 1.25 MeV. Compton and Coulomb scattering both dominate the radiation interactions in heterogeneous tissue, and the key parameter for predicting primary beam penetration, scattering, and dose deposition is the tissue electron density (electrons per cm^3). Concern for beam hardening and electronic disequilibrium effects which are prevalent at higher beam energies [42] is greatly diminished, sidestepping considerations of atomic number variations in the body [9]. Electron density information is easily extracted from CT numbers obtained in kilovoltage or megavoltage CT scans [10;110]. Interestingly, the megavoltage Compton scanner that was originally used to generate *in vivo* electron densities [10] used a cobalt-60 source. The Compton image quality [32] was soon surpassed when kilovoltage CT scanners became available.

VII. COBALT TELETHERAPY MACHINE DESIGNS

A typical early cobalt-60 teletherapy machine consisted of the following components [118]:

1. An encapsulated radioactive cobalt-60 source.
2. A source shield or housing.
3. Some device to turn the useful beam on and off (could be a rotating drum, a mercury reservoir, or sliding source drawer).
4. A diaphragm system (collimator) to limit the size of the useful beam.
5. A support mechanism by which the useful beam can be oriented with respect to the volume to be treated.
6. Ancillary devices attached to the source shield or the support mechanism to facilitate beam alignment.

Cobalt-60 teletherapy source: Figure 12 shows typical cobalt-60 source components. The original activity of the first sources was approximately 1,000 Ci although the source capsules could eventually contain up to 15,000 Ci. Prior to 1955, cobalt-60 source capsules came in all sorts of sizes and shapes. This made replacing the old sources a complex and time-consuming process. In October 1953, representatives of 14 x-ray equipment manufacturers met with representatives of the U.S. Atomic Energy Commission, Atomic Energy of Canada Limited, Oak Ridge National Laboratories and the Oak Ridge Institute of Nuclear Studies (ORINS) at the ORINS Medical Division to discuss the issue. As a result of this meeting, the source capsule shown in Figure 12 was developed and adopted as the standard configuration. This example came from Oak Ridge Associated Universities formerly known as the Oak Ridge Institute for Nuclear Studies. As such, it might date from the period when the design was being standardized [21;22;100]. In recent years, most teletherapy sources have diameters ranging between 10 to 20 mm.

Source shielding or housing: Since the radioactive source is emitting radiation all the time, the source shielding has to be designed in such a way that the radiation levels transmitted through the shielding must be low enough to be acceptable in terms of exposure to the staff working with these machines. For a source in the kilocurie range of activity, this requires an attenuation factor of about 10^6, or about 20 half-value thicknesses [118]. The usual shielding material was steel-encased lead, although some units incorporated shields of tungsten alloy or uranium. The Grimmett unit was constructed entirely out of a tungsten alloy called Hevimet, which resulted in a considerably smaller unit than lead shielded ones, allowing better maneuverability of the machine around the patient. Kerman, the radiation oncologist, noted this when he saw the John's machine but thought that the Johns' collimators were superior (see figures 2, 4, and 13). Some of the machine heads with lead shielding contained heavier

Figure 12. Cobalt-60 source capsule. The assembled source is shown on the left. The source components are shown on the right. The cobalt source itself is shown on the lower right-hand corner of the right figure and is about 2.5 cm in diameter whereas the total capsule is about 5 cm in diameter. The top of the source housing (on the left) contained an opening through which the stainless-steel source container can be seen. From [100].

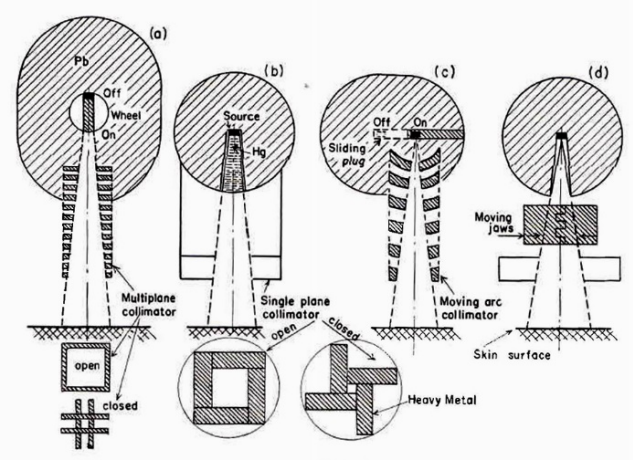

Figure 13. Four types of source shutter arrangements: (a) rotating cylinder with multiplane collimator based on the Johns and Mackay design (b) liquid mercury drawn from a reservoir (not shown), as in Eldorado A design with single plane collimator, (c) sliding drawer design (shown in more detail on the postage stamp of Figure 14) with moving arc collimator, and (d) moving jaw mechanism and single plane collimator. From reference [73]. Courtesy of Charles C Thomas Publisher, Ltd., Springfield, Illinois

metals immediately near the source, where they are more efficient in attenuating the radiation [118].

Source shutter (beam on-off mechanism): The means of turning the beam on and off has become known as the source "shutter". Various designs were used. Four examples are shown schematically in Figure 13. Figure 13(a) shows the source mounted on the circumference of a wheel near the centre of the head, so that by rotating the wheel it can be brought opposite an opening in one end of the head through which the radiation beam can emerge. Figure 13(b) shows a radiation beam emerging through a conical opening in the head. When the beam is "off", this opening is filled with liquid mercury. When the beam is turned "on", an air compressor built into the horizontal arm is started, and air pressure forces the mercury up into a reservoir. If the beam is turned "off", or if there is a power failure, the reservoir valve opens and the mercury returns, under gravity, to block the beam [71]. Figure 13(c) shows the source mounted on a sliding drawer. In the "off" position, the drawer is slid away from the collimator opening such that the radiation is shielded by the head of the machine. In the "on" position, the drawer is moved such that the source is above the collimator opening. Figure 13(d) shows a moving jaw mechanism. The first unit in Saskatchewan used the rotating cylinder and the first unit in London, Ontario, the Eldorado A, used the mercury reservoir. The sliding drawer mechanism was developed later and was probably the most frequently used mechanism in cobalt machines sold around the world. The cobalt-60 developments were recognized by the Canadian government with a postage stamp in 1988 in honor of Harold Johns. Figure 14 pictures the postage stamp with the machine using a sliding drawer mechanism.

Figure 14. Canadian postage stamp recognizing the development of cobalt-60 radiation therapy in Canada and the involvement of Harold Johns in that development. The stamp includes a schematic of a typical head of a cobalt-60 machine. The source shutter mechanism is a sliding drawer. The source is shown in the "on" position. To turn the beam "off", the source drawer is slid to the left. Also shown is the decay scheme of cobalt-60 with a beta decay with a maximum energy of 0.32 MeV followed by 2 gamma rays of 1.17 and 1.33 MeV. This style of machine was the most produced and used globally. Canada Post © 1988. Reproduced with permission.

Anecdotally, there were several reports describing some technical issues with the mercury shutter mechanism [1;53]. At the time of the development of these cobalt-60 machines, the toxic nature of mercury was not well recognized. Even in 1971, when one of the authors (JVD) began employment at the Princess Margaret Hospital in Toronto, there was still an Eldorado A in operation, along with 9 other cobalt-60 machines. However, the unit was soon taken out of service after one of the patients indicated that he could feel the radiation. In reality, he felt very small droplets of mercury from the reservoir which had developed a very minor leak, hence, causing the end of this machine's life!

Diaphragm system (collimator): A diaphragm system was needed to provide the appropriate field size necessary to cover the target volume requiring irradiation. Examples of such field definition are shown in Figures 13 and 15. Figure 15(a) shows vertical rectangular blocks. This also represents shielding provided by lead blocks placed on a tray under the head of the machine. Figure 15(b) shows

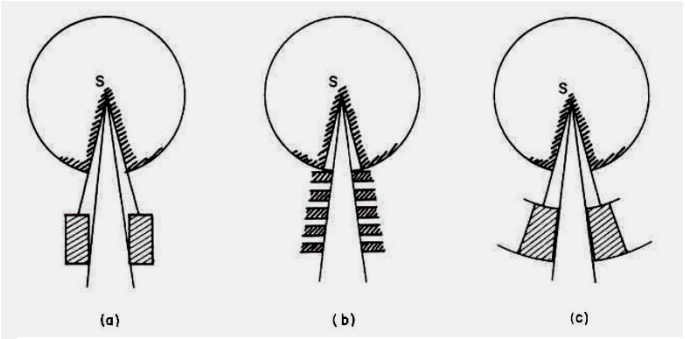

Figure 15. Idealized representation of three common types of diaphragm systems: (a) rectangular blocks, (b) multiple interlocking vanes, and (c) concentric blocks. From [118].

interleaved bars [also shown in Figure 13(a)]. The advantage of this system is that the perpendicular collimator has similar interleaved bars with the distance of the perpendicular bar pairs being only one bar thickness different, thereby minimizing the difference in geometric penumbra in the two orthogonal directions. Figure 15(c) shows the use of concentric blocks. The concern in this situation is that the perpendicular collimator has to be below or above the one shown in the figure such that the source to the bottom of the collimator distance is different by the thickness of the blocks and thus yielding a significantly different geometric penumbra in perpendicular directions. Figures 13(a) and (b) show the collimation systems as were used on the early Picker and AECL cobalt-60 machines, respectively.

Machine support mechanism: The head of the machine contains the source, the heavy shielding and beam collimation system. The machine support mechanism controls the direction and orientation of the machine head. Of the two original cobalt-60 machines, the Eldorado A had its head attached to a floor mounted column. The Saskatoon machine was ceiling mounted as shown in Figures 2 and 4. Eventually (1953) machines were developed such that the head was mounted on a rotational gantry allowing the centres of the beams to rotate about an isocentre. This permitted stationary beams to be aimed at the same point in the patient from different directions as well as dynamic rotational therapy with the beam "on" while the gantry is moving. The Grimmett-designed cobalt machine is shown in Figure 5. It also had a source mounted on a rotating cylinder and was mounted on the ceiling as in the Saskatoon unit.

Ancillary devices: A variety of ancillary devices have been developed over the years, primarily divided between those that help shape the beam and those that help direct the beam. The beam-shaping devices initially consisted primarily of lead shielding blocks placed on a shielding tray which was either mounted on a stand on the floor for machines pointing down vertically (like the Eldorado A or later the Eldorado 8) or attached in some way to the collimation system. Another major ancillary device used for many years was the wedge filter which helped shape the dose distribution inside the patient especially when multiple fields were used from various directions. Later missing tissue compensators were implemented [39;85]. Various forms of conformal shielding using Styrofoam cutouts were also developed [132].

Patient support assembly (treatment couch): Along with the development of isocentric cobalt-60 machines also capable of rotation therapy, manufacturers provided an integrated patient support assembly allowing patients to be positioned with the tumour volume generally located near the isocentre of the machine. Such assemblies can have various degrees of freedom including couch vertical motion, lateral and longitudinal motion and rotational motion about a vertical axis. The couch tops had a tennis racket-style window for minimizing intervening materials and allowing skin sparing for posterior beams, with the more modern couches being made of carbon-fiber materials which are relatively radiation transparent.

Different machine designs: Many types of cobalt-60 units have been designed over the years [17;37;44;48;54;55;65;71;72;76;77;84;112]. A partial list of manufacturers is shown in Table 4. In addition to the early units described above, other units were designed with various specialized features. For example, three different types of machines were developed and custom-built at the Princess Margaret Hospital/Ontario Cancer Institute in Toronto in collaboration with Harold Johns and Jack Cunningham. The first of these was a rotational machine, which had a built-in x-ray tube in its head for therapy verification, just above the sliding source drawer [72]. With conventional simulators not having been developed yet, this machine provided treatment simulation capabilities as well as being a forerunner of "image-guided radiation therapy." Furthermore, the counterweight contained an ionization chamber fronted by a 15 cm focussing lead plug with a large number of holes angled towards the source to provide a means of removing scatter and obtaining the radiological thickness of the patient [47]. This system was later modified by one of us (JJB) to provide a rapid means of obtaining an average tissue-air ratio directly, accounting for patient densities [11], thus providing an early method of tissue density correction especially for rotational therapy.

In 1962, Jack Cunningham and Harold Johns designed and built the world's first double-headed cobalt-60 machine capable of delivering simultaneous parallel-opposed fields, an innovative machine that could take

Table 4. Partial list of manufacturers of cobalt-60 teletherapy devices. Adapted and updated from [51]. Some of the vendors no longer market cobalt-60 units or no longer exist.

Country	Company	Device
Argentina	INVAP	Therados 800, Teradi
Canada	Best Theratronics (Formerly MDS Nordion, & AECL)	Equinox & Phoenix of the Theratron line
China	Nuclear Power Institute	GWGP80, GWXJ80
Czech Republic	UJP Praha	Terabalt
Czech Republic	SKODA	Teragam
France	Cisbio International	CIRUS
India	Panacea Medical	Bhabhatron-II & 3i
Russia	Concern "Granit-Electron"	Rokus-R
United States	Advanced Medical Systems (Formerly Picker Corporation)	ATC, C/9, V9
United States	ViewRay	MRIdian System 4.1 (3 cobalt sources)

partially decayed sources from any two of the other eight or so cobalt machines at PMH and use them for another five years, generating a reasonable patient dose rate for this specific treatment modality [37]. Jack Cunningham also developed a scanning beam technique for total body irradiation using the rails on the ceiling mounted Picker unit that was originally designed by Harold Johns [38]. Later, because both total-body and half-body radiotherapy were in such high demand, a special cobalt machine (i.e., the Hemitron) was designed and built to provide very large radiation fields, 50 cm x 160 cm at 90 cm from the source and up to about 90 cm x 300 cm for patients on a stretcher near the floor [84]. The design used large collimators akin to Figure 15(c). The world's largest field tissue-air ratios were determined by one of us (JVD) [131] (up to equivalent squares of 75 cm x 75 cm) and these were incorporated in the British Journal of Radiology Supplements 17 and 25 containing central axis data for use in radiotherapy [19;20]. Clearly, cobalt-60 machine innovations by the Johns and Cunningham team persisted well after the 1950s.

Already in 1965, Takahashi in Japan described the use of multileaf collimators (MLC) and modulated delivery on a cobalt-60 unit as a precursor to today's intensity modulation radiation therapy [122]. Also, in 1965, a group at the Royal Northern Hospital in London, England pioneered conformal radiation therapy by developing cobalt techniques in which the patient was automatically positioned during rotational therapy while moving the treatment couch and machine gantry dynamically. This was known as "The Tracking Cobalt Project" [54]. With a similar intent, Proimos in Patras, Greece [105] and later Rawlinson and Cunningham in Toronto [107], described the use of synchronous shielding in a cobalt-60 beam to make the radiation beam conform to the target while avoiding critical normal tissues.

Later, MDS Nordion developed isocentric machines with options of either an 80 cm or 100 cm source-to-axis distance with high dose rates (Theratron Elite 80/100). Their comparison is described in some detail by Glasgow [51;52].

More recently, several groups have investigated the development of MLCs for cobalt teletherapy, some of which are manual devices, while others are automated with pneumatic or motorized mechanisms [7;82;116]. Prof. John Schreiner and his group in Kingston, Ontario, Canada have considered various high-precision options for cobalt-60 teletherapy including intensity modulation [114], image guidance [110;114], and tomotherapy [27;41;79]. Some of these concepts are starting to be commercialized. For example, Best Theratronics in Canada now provides an MLC as an add-on option. Panacea Medical Technologies in India offers integrated MLCs on their Bhabhatron II and Bhabhatron 3i, with the latter being fully integrated with intensity modulation and image guidance on a ring gantry.

Perhaps the most sophisticated use of cobalt-60 teletherapy is the more recent development of MRI-guided radiation therapy [81]. ViewRay, Inc. (Cleveland, Ohio, USA) has marketed a machine (MRIdian) which integrates a 0.35 T whole-body MR imaging system using a split magnet design along with a radiation therapy system on a rotating gantry, which incorporates three heads, 120° apart, with cobalt-60 sources, each with an identical doubly focussed multileaf collimator (30 leaf pairs) [28;137]. The maximum dose rate is 555 cGy/min at the isocentre. This technology has been clinically implemented with real time anatomy tracking and beam control [56]. It provides sophisticated possibilities for adaptive radiation therapy. The most recent implementation of the ViewRay MRIdian includes a single 6 MV linear accelerator system in lieu of cobalt sources [80]. The rationale given for transitioning from cobalt sources to a linac includes reduced need for inspection, replacement and disposal of cobalt sources and reduced oversight of national agencies for radioactive sources. Furthermore, today, linacs are more common in most radiotherapy centres in high-income countries. The linac system also allows higher dose rates and faster electronic variation of the pencil beam intensities and their placement. The next section provides further discussion on the historic gradual transition from cobalt to linac radiation therapy.

VIII. GROWTH AND DECLINE OF COBALT-60 TELETHERAPY

The tremendous benefits of cobalt-60 teletherapy were recognized immediately with the first use of these machines for the treatment of cancer patients. Megavoltage energy photons along with extended patient source-to-surface distances provided depth dose characteristics previously unachievable with radium isotope machines or "deep" x-ray beams. While >20 MeV betatrons had already been developed and used for radiotherapy by the late 1940s [58;60;69;75;83], these were considered too complex and too expensive for the average radiation therapy department. Under the leadership of H.E. Johns of the Physics Department at the University of Saskatchewan, Canada, an Allis-Chalmers betatron was installed mainly for research in 1948 [63]. The first cancer treatment with a betatron in Canada occurred on 29 March 1949. The betatron remained in service for 17 years until 1965, having treated only 301 patients. One of the main drawbacks was the 'exorbitant' cost per hour of operation. A betatron donut cost $3800 in 1949 ($43,000 in 2020 dollars) and generally needed to be replaced within 150 hours of usage [63].

The world's first patient treated with a medical *linear*

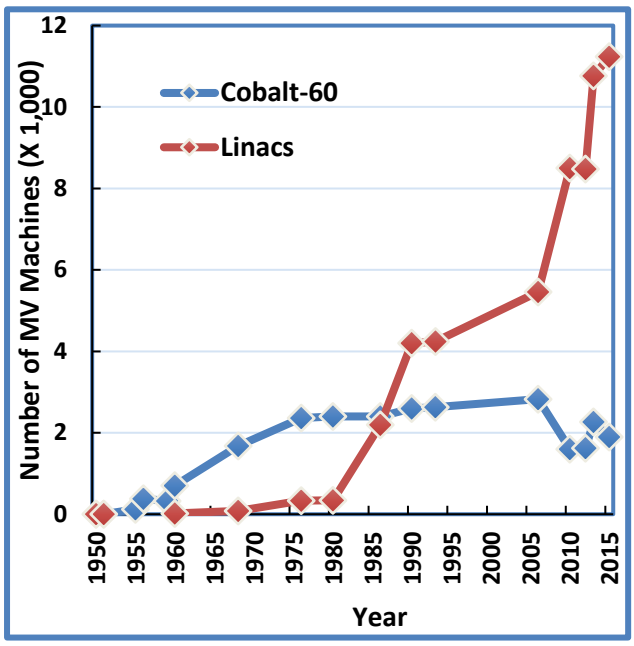

Figure 16. The global number of teletherapy cobalt-60 machines and linear accelerators versus year. The curves are based on publications from various sources of information; hence, the ragged nature of the curves; however, the trends are obvious. See text for references.

accelerator (8 MV) occurred at the Hammersmith Hospital, in London, England in August 1953 [109]. The Van de Graaff generator was also used for megavoltage radiation therapy as noted previously. In the thirty years from 1939 to 1969, no more than 136 megavoltage x-ray units were reported to be sold, whereas in the 10 years between 1951-1961, 1,120 cobalt-60 units were sold, with 422 of them in North America [109]. We have tracked the number of medical teletherapy cobalt machines and the number of medical linear accelerators in use by year based on various publications over the years [4;23;24;29;67;70;109;140]. The results are shown in Figure 16. Using some broad assumptions with significant uncertainties, we can estimate the number of patients who have been treated across the globe. Our data show that *on average*, there were about 1,600 cobalt teletherapy units per year between 1951 to 2020, i.e., over 69 years. If there are 250 treatment days per year and that on average 50 fractions are given per day (more realistically this ranges between 25 to 100 patients per day) and that each patient gets on average 19 fractions per course (This can range between 1 and 35; however, an optimal number has been shown to be 19 [136], although realistically this number has probably been less over the years), then this gives

$$69yrs \times \frac{1600units \times 250 \times 50 \frac{fractions}{day}}{19 \frac{fractions}{patient}} = 73\ million\ pts$$

Recognizing the uncertainties in these calculations, there have probably been somewhere between 50 to 100 million patients treated globally with cobalt-60 teletherapy; clearly, the clinical impact has been very significant!

IX. COBALT VERSUS LINAC: COMPETING MODALITIES

We now review the arguments normally used to justify and perpetuate this ongoing transition of technology, some of which are based on false impressions leading to an accelerated deployment of linacs. We have provided a more detailed analysis in previous publications [12;128;129]. The most common reasons in favour of accelerators include:

(1) The ALATA (As Long as it is Technologically Achievable) Principle
(2) Sharper Field Penumbra
(3) Better Conformal Dose Distributions
(4) Radiation Safety
(5) Cobalt Source Supply Chain

ALATA principle: In this age of rapidly evolving technology, it is easy to adopt exciting new products "as long as they are technologically achievable" (ALATA), without too much technical or cost analysis. The attitude is described as "Keeping up with the Joneses?". The rapid adoption of more expensive linear accelerators is driven in part by marketing hype from the manufacturers. A more rational justification is based on the acquisition of "two machines for the price of one" with x-ray and electron beam capability, variable energy, programmable beam collimation for intensity modulated radiotherapy (IMRT), and on-board image guidance (IGRT). Cobalt machines have evolved much more slowly with conservative upgrades and are therefore often viewed as a mature technology reaching their end of product life cycle.

Glasgow and Corrigan [51;52] compared the annual costs for a cobalt unit to those of a linear accelerator. The capital and operating costs amortized over a 15-year period for replacement of an AECL Theratron-780 including bunker renovations, maintenance, and licensing fees amounted to $62,000 and $100,000 per year for a Theratron-1000 and Varian 6 MV linac. A prior study by Rawlinson [106] in 1986 reported amortized costs in support of operating a cobalt unit, low energy linac, and high energy linac were ~$38,000, $123,000, and $181,000 per year, respectively. Note that all these units were equipped quite similarly before the advent of IMRT, without MLC collimation and CT image guidance. A more recent analysis [97] reported the *capital* costs for cobalt therapy unit, a low-energy linac, and high energy linac at $750,000, $2.25 M, and $4 M dollars. The annual operating costs including maintenance and source replacement were $50,000, $150,000 and $300,00 per annum. The most economical solution for mono-energetic radiotherapy with minimal

maintenance requirements is delivered by a cobalt-60 unit; this has had direct implications for low-to-middle income (LMIC) countries [6;127;140].

The many faces of penumbra: This topic is probably the least understood and the most contentious issue when it comes to the debate on cobalt versus linac purchases. X-ray beams from an accelerator undoubtedly have tighter *geometric* penumbras due to the small focal spot sizes (mms), compared with cobalt source diameters (cms). This effect is responsible for the sharpness of field edges measured "in air", including those shaped by primary or secondary collimators. However, the width of this fundamental penumbra becomes expanded "in tissue" by the lateral scattering of knock-on electrons. This physical or radiological penumbra worsens with increasing photon energy and with decreasing tissue density (Figure 17). The penumbra inside the patient is significantly and inevitably enlarged especially in lung. It should also be noted that the dose fall-off at field edges for optimized dose distributions is due mainly to the overlap of fields, and less affected by the baseline geometric penumbra of individual fields.

The obsession of having a narrow penumbra is further tempered when we consider realistic uncertainties of planning and delivering a fractionated course of radiotherapy. The first limitation occurs in treatment planning with the radiation oncologist's ability to define tissue volumes accurately or consistently [90]. Another consideration is blurring caused by the repeated positioning of the patient and possibly organ motion while the treatment beams are active. Even a "perfect" penumbra (i.e., a Dirac-delta function) will be smeared out by practical beam placement uncertainty and organ motion, such as substantial tumour movement due to the respiratory cycle. These effects are now being mitigated by the use of on-line 3-D image guidance and 4-D treatment planning. A final consideration has to do with the radiobiological response of the irradiated tissues. Tumours and normal tissues respond with a sigmoidal-shaped transform with different sensitivity and slope parameters. It is not unreasonable for cells to produce a 10% change in response to a 5% change in dose for dose levels at mid-sigmoid. The net biological effect is a *re-sharpening* of the physical penumbra. In summary, the instinctive preference for sharp geometric penumbras is intuitive but it must be tempered by the reality of radiation delivery and radiobiological considerations.

Better conformal dose distributions with increasing higher energy: The benefit of an increase in energy is often evaluated by considering depth-dose curves for single fields, dose ratios of the maximum dose and isocentric considerations for multi-field arrangements, or integral dose. However, such findings cannot be generalized for application to all tumour sites. For example, superficial diseased nodes occur in head and neck cancer and Hodgkin's disease and must be treated with a beam that has a shallow build-up layer. The choice of optimal energy therefore does not abide by a "one energy fits all" strategy. Suit [121] concluded that appropriately fitted cobalt-60 units could be "fully acceptable in the treatment of a large majority of the patients undergoing radiation treatment for carcinoma of the head-neck region, breast, and sarcomas of soft tissues of the extremities." Another study [59] showed that access to accelerators is a surrogate indicator of the overall "modern-ness" and infrastructure of a radiotherapy facility. Centres that used accelerators were apt to be well staffed and equipped with ancillary equipment like 3-D imagers, advanced treatment planning systems, electronic portal imaging, and patient immobilization systems. Much of the criticism levied at cobalt can be traced to the lack of progress in adding multi-leaf collimators and image guidance rather than beam energy *per se.* The situation is evolving as considerable advances have now been made with cost restraint [64;86;103;114]. Figure 18 provides an example of a head and neck tomotherapy

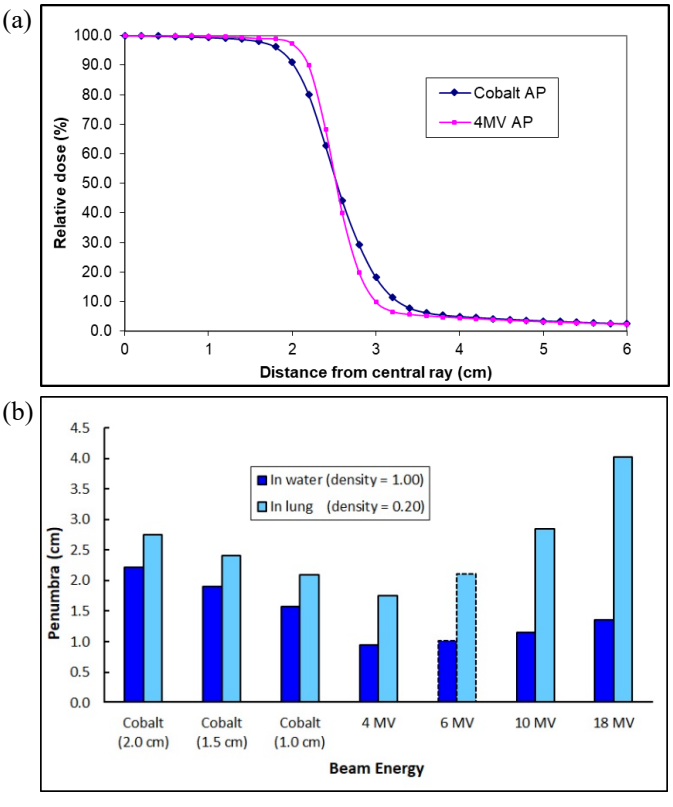

Figure 17. (a) Monte Carlo calculated dose profiles for a cobalt-60 beam and a beam of 4 MV x-rays. (b) Monte Carlo calculated beam penumbra defined as the 90-10 % width at a radiological depth of 10 cm in a homogeneous phantom of water or lung (density = 0.20 g/cc) exposed to a 5 cm × 5 cm field. Cobalt data are shown for 3 different source diameters and an SAD = 80 cm. Figures are adapted from [12]. The 6 MV data were obtained by a linear interpolation between the 4 and 10 MV data.

treatment using cobalt-60 or 6 MV x-rays. As predicted, the differences in target dose coverage and normal tissue sparing appear to be minimal. Furthermore, with multifield and rotation therapy, the differences in dose distributions as a result of different penumbra magnitudes is relatively small as shown in Figure 19. We surmise that if cobalt-60 conformal therapy and IMRT are advanced, beam energy will fade as an important variable in the retrospective analysis of clinical outcome results.

Radiation safety: Modern cobalt machines use sources with over 10 times more activity (e.g., 13,000 Ci or 500 TBq) than the original sources to yield a dose rate of over 200 cGy per minute at an SAD of 100 cm. The advantage of radioactivity is a very predictable and constant dose rate except for monthly source decay corrections. In practice, the cobalt source is retracted into a bulky head assembly when not in use (e.g., Figure 13(c)), but there is a risk of a radiation incident if the source "gets stuck" in the "on" position. Personnel are trained to cope safely with this type of emergency. The shielding attenuates the continuous stream of emitted gamma rays to protect medical personnel in the treatment room and the public beyond. Radioactive sources cannot be switched off and pose human and ecological risks while being transported, placed into medical devices and hospital facilities, and at disposal time. Considering that thousands of cobalt medical sources have been shipped incident-free over past decades by a Canadian company to over 65 countries, source transportation by conscientious manufacturers is a very safe practice. The radioactive source is always radiating, however, whereas a linac beam can be interrupted at a moment's notice, ignoring the low induced radioactivity in collimating and room structures for beams above 10 MV. The production of x-rays is therefore more switchable, although there have been serious accidents with accelerators due to failure of hardware and software controls. The issue of source disposal is of substantial concern if inadequate legislation is in place, as evidenced by incidents that have occurred in Mexico and Brazil [13;99]. These are exceptional occurrences attributed to untrained, incompetent, or unscrupulous individuals.

The theft of a source by unauthorized persons or groups could lead to the fabrication of "dirty" radiological bombs with grave consequences. Following the 11 September 2001 terrorist events in the United States, security measures were enhanced for all facilities housing intense radioactive sources. In 2015, government proposals (yet unapproved) were tabled to phase out *all* radioisotope sources [97]. The intended and unintended consequences of such a directive are immense for the American population and for the rest of the world [31]. In a later section, we describe general applications of cobalt-60 beyond radiotherapy including the irradiation of food, medical devices, blood irradiation for tissue allografts, and consumer products. The total abolishment of cobalt-60 sterilization, without a cost-effective substitute linac technology would lead to a catastrophic global disruption of the food and medical supply chains. Radiotherapy in many low-to-middle-income countries with perhaps 2,000 cobalt teletherapy units, which service a large percentage of the world population, would be in jeopardy. A shift of cobalt-60 activation and manufacturing plants to other countries with less stringent radiation regulations would aggravate security risks on a world scale.

Cobalt-59 supply: The current cost of a cobalt therapy source is driven only partially by the cost of cobalt-59 metal ($30.00 per kilogram), which is expected to rise dramatically within this decade because of heavy demand for electric vehicle lithium-ion batteries. This may impact the cost of cobalt units to a minor extent because the cost of cobalt-59 material is a minor contributor to the overall cost of a therapy machine. Production of a radioactive source requires access to costly nuclear reactor facilities. For example, a cobalt source replacement generally costs between $100,000 to $200,000 [97]. The electric vehicle market is unlikely to impact the cost of a therapy unit, but *it could halt their production line*. It is projected that 10 to 20 million electric cars will be produced *each year*

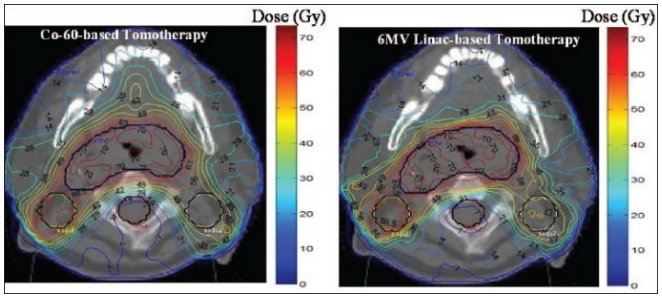

Figure 18. Tomotherapy distributions using cobalt-60 or 6 MV x-rays. With permission from [79].

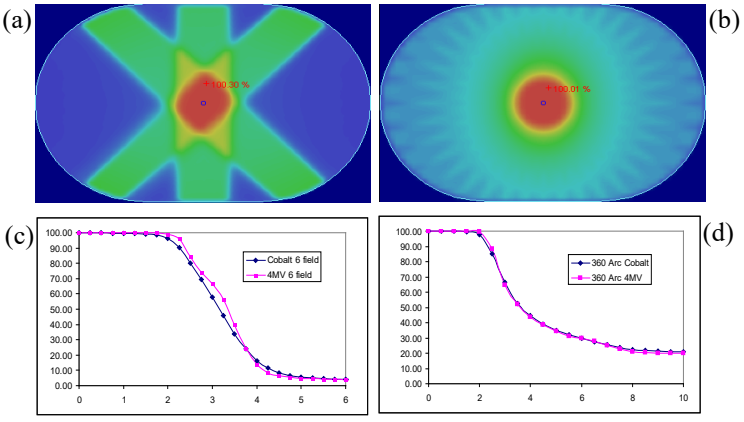

Figure 19. Cobalt-60 dose distributions for: (a) 6-field, and (b) 360° rotational techniques. Below each distribution (c and d) is a plot of the corresponding mid-plane horizontal dose profile (% dose versus distance from the central ray in cm) with a comparison to that achieved with 4 MV x-ray beams, which has the sharpest single-beam penumbra as shown in Figure 17. From [12].

starting in 2025, just 5 years from now. Each car battery requires 10 kg of cobalt and, hence, electric vehicle manufacturing will need 100,000 to 200,000 metric tons of cobalt metal *per year*, comparable to the entire world's current supply (140,000 metric tons per year) [124]. The annual supply will clearly need to escalate in response to the automotive industry or cause a serious deficit for medical needs including sterilization and radiotherapy. This could clearly become a serious issue within this decade; medical and automotive industries need to reach an agreement on the sharing of the world's supply of cobalt-59. In parallel, the development of alternative battery designs that avoid the use of cobalt will likely eventually reduce the demand.

The discussions about the pros and cons of cobalt-60 teletherapy in comparison to radiotherapy with linear accelerators has been on-going for many years [12;62;68;102;128;129]. Table 5 provides an overall, abbreviated, high-level summary of these factors of comparison between cobalt and linacs [68;128]. Note that as a high-level view and as indicated by the earlier discussion, there are a lot of details that provide variations on these broad perspectives.

To summarize these considerations, the general arguments against cobalt are large geometric penumbra, changing dose rate due to source decay, source replacement every five years, radiation safety concerns with a radioactive source that emits radiation continuously, security concerns regarding the radioactive source and possible malicious abuse, lack of modern technology such as built-in multileaf collimator (MLC), shallower depth of penetration, and radiation safety concerns associated with appropriate source disposal. In contrast, cobalt offers lower cost and greater simplicity for less sophisticated techniques.

X. OTHER USES OF COBALT-60

Cobalt-60 sources have been used for several other clinical applications in addition to external beam teletherapy. Some examples are summarized here.

Gamma unit for stereotactic radiosurgery: It was already in the 1950s that Swedish professors Borje Larsson of the Gustaf Werner Institute, University of Uppsala, and Lars Leksell at the Karolinska Institute in Stockholm, Sweden, began to think about combining proton beams with stereotactic devices for small targets in the brain. They gave up on this approach because it was complex and costly. Instead, in 1967, they designed the first Gamma Knife device using cobalt-60 as the source of energy and had it constructed. This new focused radiation therapy technique became known as "stereotactic radiosurgery." The prototype unit was in clinical use for 12 years in Sweden, with specific clinical applications for functional neurological surgery, e.g., for treatment of patients with pain, movement disorders, and certain behavioral disorders.

Prof. Leksell and his collaborators manufactured a

Table 5. Abbreviated comparison of cobalt and linacs

Issue	Cobalt	Linac
Technique types	Simpler	More complex
Penumbra	Larger (1-2 cm)	Smaller (~1 cm)
Dose at 10 cm	Lower (~56%)	Higher (67-80%)
Dose uniformity	Not flat for large fields	Flat for large fields
Depth of max. dose	~0.5 cm	1.0-3.5 cm
Impact of surface contour and density variations	Significant	Lower (4-10 MV). Higher (>10 MV) due to electron transport in lung
Relative dose to bone	0.96-1.14	0.97-1.04
Dose rate	1.2-2.6 Gy/min	2.0-25 Gy/min
Patient collimator distance	30-50 cm	~50 cm
Isocentre height	~115-136 cm	~110-134 cm
Photon source	Gamma rays – decays ~1%/month	X-rays, constant dose rate
Output	Stable – constant radioactive decay	Possibly variable due to electronic instabilities
Beam shaping/MLC	Not standard, add on MLC available for some products	MLC optional
IMRT/VMAT capable	Not standard	Optional
IGRT capable	Not standard	Optional
Local infrastructure	Simple power source	Stable power source
Room requirements	Simple	Possible air conditioning, chilled water
Shielding	Less	More
Service availability	Important	Important
IT infrastructure	Basic	Important
Source transport/ disposal	Every ~5 yrs, Stuck source risks	
Cardiac implantable devices	No risk except radiation dose	Dose risks & possible electromagnetic interference
Security	Source is possible security risk (e.g., dirty bombs)	No radioactive source
Capital cost: Building	Lower than linac	Dependent on energy and options
Capital cost: Equipment	Less expensive	Dependent on energies & options
Personnel	Less for simpler techniques	Dependent on options and techniques
Maintenance	Lower cost	Higher cost

second Gamma Knife in 1975, which was installed at the Karolinska Institute for its neurosurgical service there. Subsequent units, which were built in the early 1980s, were installed in Buenos Aires, Argentina; Sheffield, England; the University of Pittsburgh (through the efforts of Lundsford et al [93]); and the University of Virginia.

With the development of stereotactic angiography, arteriovenous malformations (AVMs) and cranial-based tumours became appropriate targets for stereotactic irradiation. In the 1980s, an increasing number of patients had radiosurgery for AVMs, some benign tumors, and some small-volume malignant tumors. Currently, based on the information on the Elekta website, over one million patients have undergone Gamma Knife radiosurgery and over 75,000 patients per year receive the treatment.

While the original Leksell prototype unit used 179 cobalt-60 sources arranged over a spherical segment of 60° x 160°, the later U, B and B-2 gamma units are manufactured by Elekta (Stockholm, Sweden) and incorporate 201 sources housed in the central body of the unit. These sources produce 201 collimated beams directed at a single focal point at a source-focus distance of ~40 cm (Figure 20). The main components of these gamma units are: the radiation unit with upper hemispherical shield and central body; the operating table and sliding cradle; a set of collimator helmets; and a control unit [104].

In the U, B, and C models of the Gamma Knife, the beam collimation is split between an internal collimation and a removable external helmet-based collimation system. Each external collimator helmet has an array of removable tungsten collimators (one for each source) with circular apertures that are used to create different diameter fields at the focus point. Four, 8, 14, and 18 mm collimator helmets are available. A subset of the collimators may be removed and replaced with solid tungsten "plugs" to block individual beams in cases where additional shielding is required. Modification of the isodose distribution is achieved by using combinations of isocentres using different collimators, different stereotactic locations, and differing dwell times.

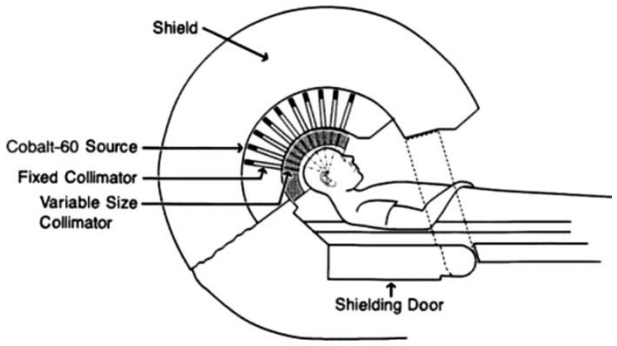

Figure 20. A schematic of the cross section of the GammaKnife U. It shows the structure of the central body in which the 201 cobalt-60 sources are positioned.

In the new Gamma Knife Perfexion, the external helmet collimators have been replaced by a single internal collimation system. In the Perfexion, the cobalt-60 sources move along the collimator body to locations where 4, 8, and 16 mm apertures have been created. (The above descriptions of the gamma units are largely extracted from [104;125].)

The most recent model of the Gamma Knife series is the Icon (Figure 21), which has the same delivery and patient positioning system as the Perfexion, but has the addition of a cone-beam computed tomography imaging arm and an intrafraction motion management system [45].

Brachytherapy: Cobalt-60 needles were used for a short time after the second world war but fell out of favour later on [8;14;50]. In 1962, Walstam introduced the first concept of a remote afterloader equipped with cobalt-60 [133]. Remote controlled afterloading was introduced clinically in the 1970s mostly using caesium-137 sources for low-dose rate treatments. In 2003, Eckert & Ziegler BEBIG successfully designed and introduced the first miniaturized cobalt-60 source. Since then they have sold over 270 high-dose rate (HDR) brachytherapy systems equipped with cobalt-60 sources.

In 1988, Mesina et al described their acceptance testing of the Nucletron Selectron HDR cobalt-60 unit [94]. HDR brachytherapy has most often been used with iridium-192 sources that have to be replaced on regular basis several times per year because of its relatively short half life of 74 days. Hayman et al performed a cost comparison between the use of cobalt-60 and iridium-192 HDR treatments over a 10 year period and concluded that there were significant economic benefits of cobalt-60 over iridium-192 and that there was no significant difference between these two isotopes in dose prescription or

Figure 21. Most recent version of Elekta's Gamma Knife Icon which includes cone-beam CT image guidance capabilities.

treatment planning [61]. A separate dosimetric comparison concluded that there are no clinical advantages or disadvantages of cobalt-60 versus iridium-192 but there are potential logistical advantages of cobalt-60 due to its longer half life, making it an interesting alternative especially in low-to-middle income countries where source replacements can be a significant administrative challenge [120].

While surgical management with enucleation was the primary treatment for uveal melanoma (UM) for over 100 years, brachytherapy has now become a standard of care as an eye-preserving treatment modality [18]. Chronologically, the following isotopes have been used in rings or plaques [18]: radon-222 encapsulated in gold seeds (began 1939) [119], cobalt-60 radioactive scleral plaques (Stallard reported on 99 patients treated up to 1964 [119]), ruthenium-106 β-emitter, iodine-125 plaques, and palladium-103 seeds. Stallard's cobalt-60 radioactive plaque technique revolutionized treatment and was also used for retinoblastoma patients [18]. The UM patients were treated with cobalt-loaded circular, crescentic, or semicircular applicators that were sutured to the sclera over the neoplasm with a 1 mm margin. Most of the patients received a radiation dose of 20,000–40,000 R at the tumor base over 7–14 days; the optimal dose was still under investigation. In 1984, it was reported that the "average" UM patient treated with cobalt-plaque therapy did not completely regress to a flat, depigmented scar, leaving concern that the remaining tumour may be viable and capable of metastasizing [18]. Furthermore, cobalt-60 plaques are high in energy and cannot be shielded effectively on their external surface, as other isotopes could. By 1985, cobalt plaques were no longer regularly used in London, England [18].

Gamma irradiators for research and medical purposes: Self-shielded cobalt-60 gamma irradiators are in use in many hospitals around the world. These units can be placed in any room without adding shielding. They date back to 1959 and can be used by researchers wishing to perform mutation and other biological effects studies; studies in the area of radiation chemistry; radiation dosimeter testing; research in the sterilization of food materials, soils, sediments and other media; gamma radiation damage studies; and for many other applications [101]. They can be used to irradiate blood used for blood transfusions for immuno-deficient and immuno-suppressed patients to minimize the impact of graft-versus host disease, possibly in association with bone marrow transplants. Already in the 1960s, these irradiators were used for extracorporeal blood irradiation where a portion of a patient's blood was shunted through the irradiation field of the gamma irradiator. Applications included study of: (1) radiation response of circulating elements of peripheral blood, (2) radiation injury of circulating plasma proteins, (3) kinetics of blood cell production, particularly the lymphocyte type, (4) therapy of selected leukemias, and (5) cardiac output and flow through selected organs by radioisotope techniques [30;117]. These irradiators can contain cobalt-60 activities up to 24 kCi (e.g., for the MDS Nordion Gammacell 220). Today many of these gamma irradiators use caesium-137 sources although the cobalt-60 option is still available.

Other cobalt-60 uses: There are a variety of other applications using cobalt-60 although these are not medically related, other than sterilization of medical products; hence, they will only be listed here without much explanation:

- *Industrial radiography* as a form of non-destructive testing for assessing metal welds in pipes and other metal containers, especially for the oil exploration industry and in the printing industry to monitor the flow of inks and thickness of paper
- *Food irradiation* for extending the shelf life of various fruits and vegetables. This started at AECL in Canada in 1961. Even a mobile potato crop irradiator with 16 kCi of cobalt-60 was proposed [87]
- *Sterilization* of medical supplies and devices, e.g., surgical gowns, latex gloves, catheters, scalpels, bandages and implants
- *Chemical processes*, e.g., polymerization of plastics
- *Decontamination* of cosmetic raw material and applicators
- *Treatment of fresh produce* to prevent the spread of disease and consumption of crop by invasive species of insects
- *Preservation* of cultural heritage items
- *Treatment of gemstones* to improve their colour.

XII. SUMMARY AND CONCLUSIONS

The development of cobalt-60 radiation therapy for cancer patients beginning in 1951 was a historic breakthrough, moving radiation therapy into a new age with very significant improvements in patient outcomes both from the perspective of tumour control and reduced normal tissue complications, including a great reduction in skin reactions. While we estimate that between 50 to 100 million patients have benefited from cobalt-60 treatments since its implementation into clinical practice, it is not easy to estimate what impact cobalt-60 has had on quality-adjusted life years. In the meantime, linear accelerator developments have competed with cobalt-60 to the extent that in the mid-1980s, the number of linear accelerators surpassed the number of cobalt-60 machines (Figure 16). Furthermore, the technological advances on linear accelerators significantly increased their capabilities with IMRT and IGRT. Similar developments on cobalt-60 machines occurred decades later, leaving cobalt-60 teletherapy far behind for many years in terms

of technical capabilities. Furthermore, the concerns about cobalt-60 being a radioactive source and the possibility of terrorist activity, in the context of using these sources as "dirty bombs", has prompted a mentality of removing these sources from usage as much as possible. This awareness became more acute with the terrorist activities that occurred on "9/11" 2001.

One of the very significant advantages of cobalt-60 therapy in earlier days was its simplicity and its relatively low cost compared to the less stable and more complex linear accelerators. However, as the new options of MLCs, IMRT and IGRT are added and as linear accelerator technology has provided more stable beams and improved reliability, this relative simplicity is fading. Thus, the combined concerns of greater complexity for cobalt-60 machines with automated collimation and on-board imaging technologies, enhanced stability of linear accelerators, and the security concerns for cobalt-60 sources have significantly reduced the remaining advantages of cobalt-60 compared to linacs.

In summary, we have reviewed the post-war developments of cobalt-60 radiotherapy equipment. This was truly an international effort, driven largely by the nuclear reactor technology that emerged after the war and the human appetite for using radiation as a peaceful and benevolent agent for curing a major disease threat. Cobalt-60 has given hope for a normal life to over 50 million cancer patients since 27 October 1951. More importantly cobalt therapy provided a stimulus for catapulting megavoltage therapy forward, which is the current standard of practice in high-income countries (HICs). Cobalt-60 radiation therapy continues to evolve and play a role in LMICs dealing with 70% of world cancer deaths [138] but only using 35% of the world's radiation therapy facilities; or stated another way, LMICs have 0.7 machines per million population versus 7.6 machines per million for HICs [40]. Within the African continent, around half of the countries have no radiotherapy services and most of those that have cannot adequately cover the population which needs them [98]. The cost-effectiveness and ease of maintenance of cobalt units has contributed to the cause of treating cancer worldwide. While treatment techniques will improve as a new generation of IMRT-ready cobalt units emerge, security of cobalt installations and proper disposal of radioactive sources remain a genuine concern and top priority for strict government oversight. The future supply of cobalt metal will be drained by the electric automotive revolution, perhaps as early as 2025. It might enhance the shift to accelerators, possibly continuing the stress on LMICs.

Clinical outcomes in terms of disease-free survival and fewer treatment complications continue to improve with image-guided IMRT, VMAT, high precision radiosurgery, along with automation and artificial intelligence. There undoubtedly will be new imaging and accelerator developments in the future. One can dream of high-LET beams such as carbon ions eventually becoming available for national use in every country or that the recent excitement about FLASH radiation therapy [15;16] will provide new, cost-effective treatment modalities that can be readily implemented globally.

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THE MANY STEPS AND EVOLUTION IN THE DEVELOPMENT OF COMPUTED TOMOGRAPHY TECHNOLOGY AND IMAGING METHODS, THE QUEST FOR ENHANCED VISIBILITY

The First Fifty Years

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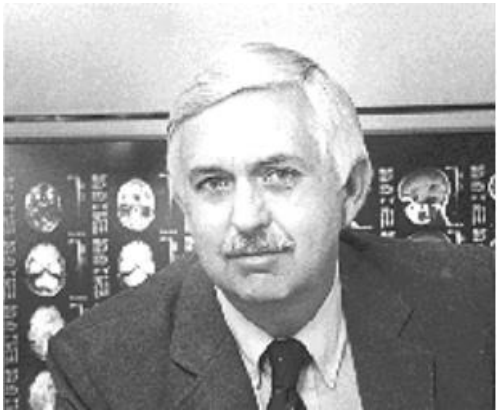
- *Abstract*— **Computed Tomography (CT) is considered the second most significant contribution of physics and technology to medicine following Roentgen's discovery and introduction of x-ray imaging, radiography. . CT is an x-ray imaging process but greatly extends the scope of structures, functions, and conditions within a human body that can be visualized for medical diagnosis. Compared to radiography CT provides two major advantages, It is a tomographic method that provides close viewing (within millimeters) of objects and locations within a human body without interference from overlying body sections. The second value is its high contrast sensitivity, the ability to produce visible contrast among different soft tissues, even when enclosed within a dense bony skull. The production of CT images is a sequence of two distinct phases. The first is scanning an x-ray beam around a patient body and measuring the total attenuation along different pathways through the slice of tissue that is to be imaged. This produces a data set consisting of large number (1000s) of measurements. The second phase is a mathematical process of calculating, generally referred to as "reconstructing" a digital image from the acquired data set. Allan Cormack, a physicist, first developed a mathematical process for calculating the distribution of x-ray attenuation values throughout a simulated body section. Godfrey Hounsfield, an engineer on the staff of EMI, developed the technology for scanning and measuring x-ray attenuation along many pathways through a human body. He also developed a mathematical process for reconstructing tomographic images. One of the first, an image of the brain showing a tumor while enclosed in the skull introduced CT to the world as a new and revolutionary diagnostic method. In 1979 Cormack and Hounsfield jointly received the Nobel Prize. EMI manufactured the first CT systems that were limited to imaging the head. Robert Ledley was to soon develop the who body scanner. Two major limitations with the scanners were less than desired image quality and the long time (minutes) required to scan and produce an image, what was to follow were many technical improvements producing different "generations" of CT scanners each generally providing faster data acquisition. Much of this progress was associated with the advances in design of the detectors. The first was a single small detector, followed by multiple detectors and fan-shaped x-ray beams that could make more measurements simultaneously and faster acquisitions. A major advancement was the multi-row detectors that introduced multi-slice imaging. A major and essentially concluding step in the development of general purpose clinical scanners was the invention and development of spiral scanning by Willi Kalender. This rapidly produced volume, rather than slice, data sets and opened up many possibilities for image reconstruction. Along with the many developments to provide improved image quality and faster imaging there were significant advances in radiation dose management and scanners for special clinical applications including dentistry and breast imaging.**
- *Keywords*— **tomography, reconstruction, digital, scanning, detectors.**

I. INTRODUCTION AND OVERVIEW



As a clinical medical physicist and educator it has been my opportunity to work with computed tomography from its beginning and on throughout my career. My introduction was a course in the EMI factory where Hounsfield developed the first system in preparation for installing one of the early scanners in my institution, Emory University Hospital in Atlanta. That was to become one of my major projects. Continuing from the first scanner on to the present the capabilities and complexity of CT have expanded and so have the role and responsibilities of medical physicists. As we continue to apply our physics knowledge and experience supporting CT as a highly valuable clinical modality and provide education for future generations there is value in knowing the history leading up to the technology we use today. It was a step-by-step process by many physicists and engineers that is a major part of our heritage. That is the journey that I share with you here.

The introduction of computed tomography (CT) for medical imaging in 1976 is sometimes considered as one of the greatest contributions to diagnostic medicine, second to x-ray imaging (radiography and fluoroscopy) by Roentgen in 1894. Both are physical methods developed by physicists and engineers, with the significance of each being recognized with Nobel Prizes. Both are forms of x-ray imaging; but the difference is how the images are formed. One method simply passes an x-ray beam through a section of a human body and projects shadows. The other (CT) is a much more complex process of two distinct phases. The first phase passes x-radiation through in the plane of slices within a body and measures accumulative attenuations from many different directions. This produces the sets of "scan data." The next and evolutionary phase is the mathematical "reconstruction" of an image of the slice of body section from the scan data.
The fundamentals of mathematical image reconstruction applied to tomographic body sections were developed over the years with several innovative contributions by mathematicians and physicists. However it was the development and availability of digital technology and computers that made it possible for an engineer, Geoffrey Hounsfield, to develop the first computed tomography (CT) to be used for medical diagnosis.

The development and clinical application of x-ray CT was to be a major evolution in the field of medicine. Physicians were being presented with a completely new view of the human body, tomograms. There was now the need to learn and teach cross-sectional anatomy. It was now possible to "get in close," within a few millimeters, and view anatomical features without interference from other body sections. In several ways, scientifically, technically, and medically, x-ray CT was to be an introduction to the many other "computed tomography" imaging modalities that were based on image reconstruction, including MRI, SPECT, and PE--each using computed tomographic imaging but providing visualization of very different tissue and functional characteristics.

Our specific interest here is x-ray computed tomography. From its initial development and introduction for medical imaging in 1976 it has continuously evolved with many innovations with the goal of enhanced visualization of structures and conditions within the human body and with considerations for radiation exposure and associated risks--two often opposing goals because several aspects of image quality are directly or indirectly dependent on the quantity of radiation used in the imaging process.

The characteristic of CT that has been a driving force for continuing physics research and technological development is that it is a sequential imaging process requiring a series of x-ray attenuation measurements which is time consuming. A measurement of progress and advancement over the years has been scanning speed and the time required to produce an image. This is significant for several reasons including patient throughput and ability to image with reduced patient motion interference. An associated factor is that image quality, especially detail (spatial resolution) and noise are dependent on the number of measurements (samples) in a scan and data acquisition. It is the combination of increased image quality (clinical visibility), limiting radiation dose, and reduced acquisition time that has resulted from the efforts of many physicists and engineers for now a half century. Those contributions are extensively recorded in the scientific literature. Books and review articles focusing on the history, as identified in the References and Bibliography, provide the details of this major era of medical physics and the associated professions.

Our purpose here is not to repeat the many excellent publications, both scientific reports and historical reviews, but to provide a guide and overview through the continuing evolution of computed tomography physics and technology. The Bibliography at the end of this article identifies publications on the history of CT. Two of the most comprehensive are the books, *From the Watching of the Shadows* by S Webb and *Computed Tomography* by W Kalender. Here we will consider the vision and motivation of the contributors, the relationship and dependence on other scientific and technological developments, and the efforts to increase the value of CT as a major medical method for diagnosis and guiding therapeutic procedures.

The history of computed tomography is not just a series of events along a timeline. It is a comprehensive and dynamic process of expanding and enhancing the clinical value and capabilities of x-ray imaging. It is a continuing *step-by-step* process of developments and innovations increasing the quality and capabilities of CT as a medical procedure. The steps range from small to large with each providing something of value. As we read and view images and illustrations of those developments let's give attention to the advances in imaging capabilities each provides. That is the theme we will follow.

The goal of medical physics and engineering research and development with respect to imaging is increasing the range of visibility of structures, functions, and conditions within the human body, managing risks, and availability as needed to enhance the practice of medicine and clinical care of patients around the world…Step by Step.

II. X-RAY IMAGING

The first and giant step to this goal was the discovery and development of x-ray imaging. It is the foundation of our exploration of medical imaging physics and provides context for computed tomography as an evolutionary application of physics in the field of medicine.

X-radiation provided the first method for imaging the internal structures of the human body for medical purposes. It began with Roentgen's discovery, intense research, and demonstration of its medical capabilities in 1897 and illustrated in Fig.1.

Fig.1. Roentgen's lecture and demonstration of the "new kind of radiation" by producing an image of the hand of the University's anatomy professor.

With Roentgen's early work and as news of the x-ray process spread around the world the human hand was the common anatomical region to be imaged. It was thin and relatively easy for the x-radiation to penetrate and the bones provided high contrast in relation to the soft tissue. This is demonstrated in an image of the author's hand shown in Fig.2.

Fig.2. An x-ray image of the Author's hand simulating what is believed to have been a significant event in Roentgen's discovery.

Roentgen reports that he had observed and was investigating the penetrating characteristics of the new radiation (Ref.1). When he was holding a coin to see if it would be penetrated he saw the shadow image of the bones in his hand. Perhaps we can consider this the "birth" of medical x-ray imaging.

Projection X-ray Imaging

Producing images by projecting an x-ray beam through a region of the human body was to become one of the most significant medical procedures for well over a century. This was the modalities of radiography and fluoroscopy. The history of the developments and evolution of these methods with an emphasis on the physics and technology is described in previous publications (Ref. 2, 3, 4, and 5).

Even though projection imaging was a revolutionary and extremely valuable contribution to medicine, it had two characteristics that limited clinical applications and motivated research and development for methods that could provide greater visibility of anatomical structures and clinical conditions within the body. With the projection method the images of the internal objects are "stacked" or overlaid with some covering or blocking the view of others. While this type of image is appropriate and extremely valuable for some clinical applications--the chest is an example--it has major limitations for imaging the human head. The soft tissue brain enclosed in the bony skull is essentially invisible in a conventional radiograph.

The other characteristic of the projection method is relatively low *contrast sensitivity*, especially when compared to some of the future methods including CT and MRI. The contrast sensitivity of an imaging procedure is the relationship between visible contrast in an image and the physical contrast among the soft tissues and the fluids within the body. A major challenge is that soft tissues and body fluids, especially blood, have close physical density and atomic number (Z) values that are the source of physical contrast that forms images. Over the years there has been continuing research and development to address this limitation. One has been to design x-ray spectra that are optimized to produce a high contrast-to-patient dose relationship. This has been especially significant in mammography by using combinations of x-ray tube anode materials, filter materials, and KV values. Another has been the development of contrast media that can be administered to a patient to provide temporary contrast specially to visualize the blood circulatory system, urinary track, and digestive system. A historical review of those developments has been previously published. (Ref. 5).

Classical Tomography

Almost from the beginning of x-ray imaging the limitation to visibility of some anatomical structures by overlying regions within the body was recognized as a problem to be solved. This introduced the need to image selected layers or slices through the body that was to become the process of *tomography.* The limitation was the x-ray projection process produced images of a 3D volume anatomical region…not selected slices. Research and development resulted in a series of technical devices and methods for producing images of slices, tomograms, with projection imaging. Webb provides an excellent historical review. (See Bibliography).

The many tomographic methods developed were based on the same physical principle. That was to use motion during the x-ray exposure to selectively blur the anatomical regions other than in the slice of interest. These regions would be in the image but blurred and hopefully less visible than the details in the slice of interest. Of the many methods developed and tried the one illustrated in Fig.3 was to become the most widely used and common tomographic procedure up until the development of computed tomography.

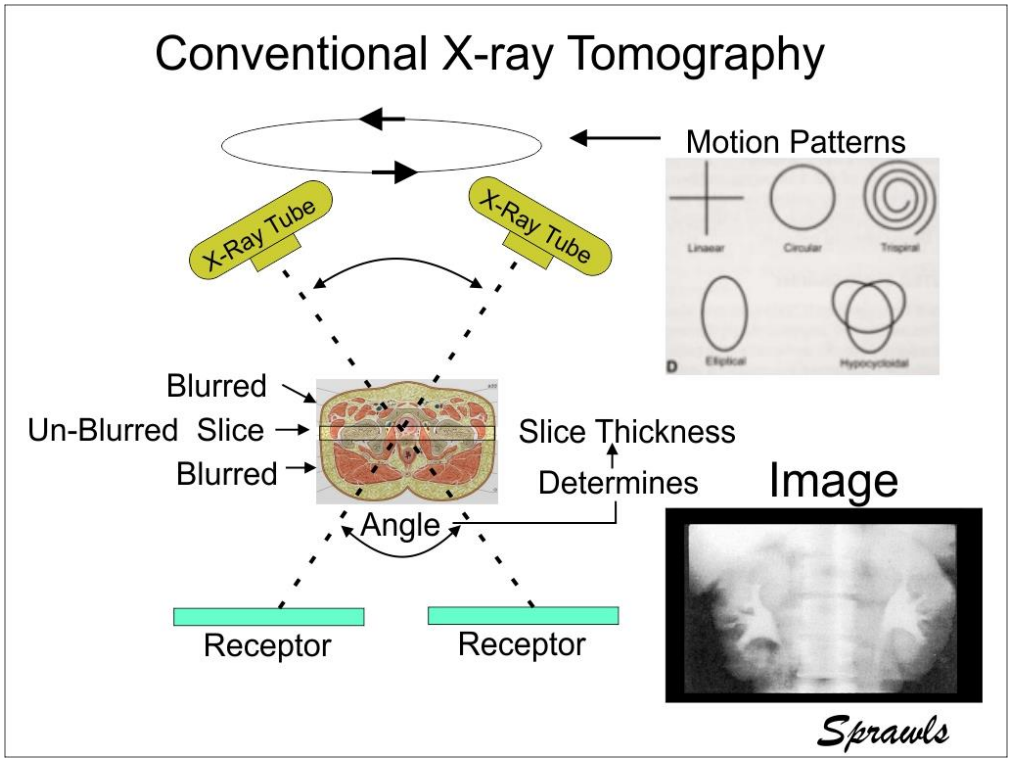


Fig.3. An overview of the conventional x-ray tomography process.

The x-ray source and the image receptor, usually film and intensifying screens, were mounted on a mechanism that rotated them around a "pivot point" located in the slice that was to be imaged without blurring and with good detail. The motion of the x-ray beam blurred the image of the anatomical regions on each side of the slice. This process does not eliminate the adjacent regions from the image; it just blurs them in relation to the slice that is being imaged. The expectation is that the anatomical structures within the slice will become more visible. The image in Fig.3 is an example in which the visualization of the kidneys is enhanced. In addition to the most widely used method illustrated in Fig. 3 other approaches included having the patient on a rotating stool during the x-ray exposure synchronized with a rotating image receptor.

Depending on the design of the system there are adjustments that are made by the operator for specific clinical procedures. The slice thickness is controlled by adjusting the angle of movement. This tomographic method does not produce a well-defined slice with a specific thickness. The blurring increases with distance out from the location of the pivot point. Slice thickness is a somewhat arbitrary designation of the area in which there is not significant blurring, at least compared to the anatomical areas that are being blurred to reduce their visibility. To enhance the blurring of some anatomical features a variety of motion patterns could be selected.

The production of tomographic images using an x-ray beam projected through a full anatomical region and blurring the interfering layers with motion was a valuable clinical procedure for many years and benefited from a series of innovations and developments as described in the references cited above. It was a significant step to increasing visibility of some specific anatomical structures, such as in the abdomen or pelvic regions. However, not just the slice of interest was included in the image. There were the overlying body sections, somewhat blurred, but interfering with the visibility of details within the slice being imaged.

That was the challenge to be overcome and the solution was to be provided by computed tomography (CT).

It would require a method in which an image could be formed with an x-ray beam limited just to the tissue slice of interest without passing through and producing images of the overlaying body sections as illustrated in Fig. 4.

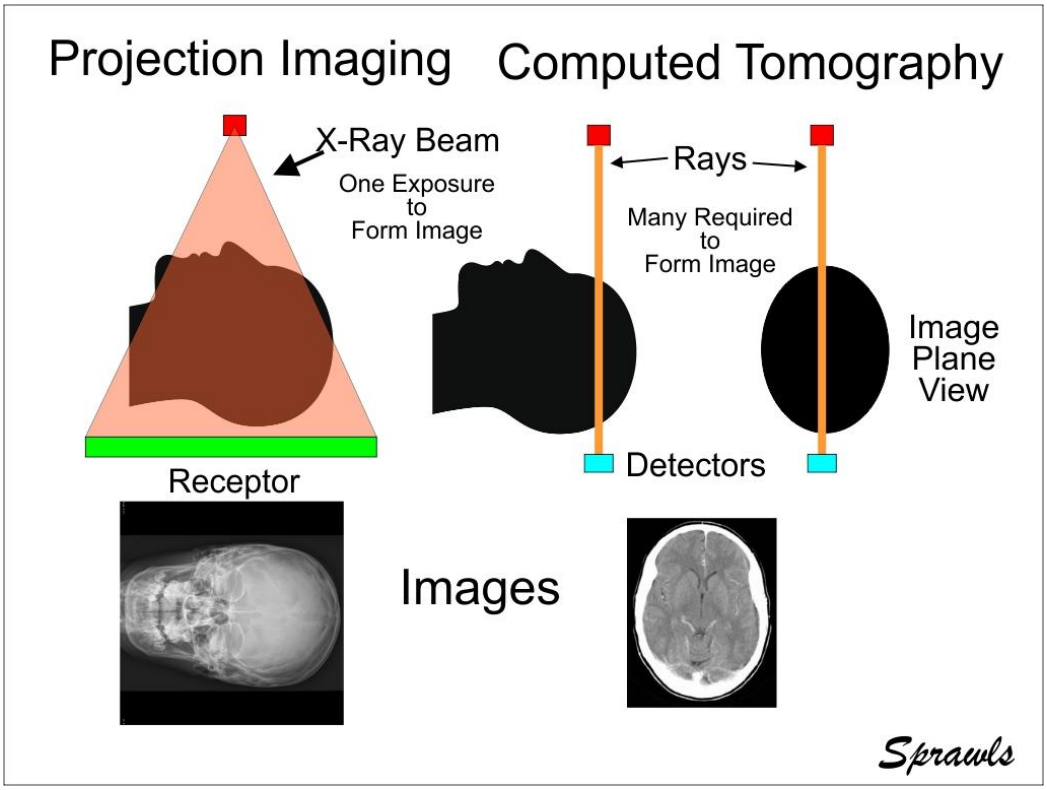


Fig.4. Comparing projection x-ray imaging, radiography, to computed tomography with respect to the passage of the x-ray beam through a region of the human body.

This illustration shows the major difference between the two imaging methods. With the projection method the x-ray beam is normal (90 degrees) to the plane of the image and forms the image directly by casting shadows. When the x-ray beam passes through the tissue slice in the plane of the image it cannot form an image directly. It requires that an image be "reconstructed" from x-ray attenuation measurements made by passing an x-ray beam through the body in the plane of the slice to be imaged. That is the principle and process of computed tomography.

The major factor associated with CT that has motivated many years of continuing research and development is the acquisition of the x-ray image by making many individual measurements or samples with small "rays" passing through the body. This is a time consuming process. A major effort has been to speed up the acquisition process generally by developing systems that make more and more simultaneous measurements. This has reduced acquisition times for one image from several minutes down to a fraction of a second. It has been the technology developed to reduce acquisition time that defines the different "generations" that will be described later.

III. FROM CASTING SHADOWS TO RECONSTRUCTING IMAGES

With the x-ray projection methods images are shadows of internal body structures formed by projecting an x-ray beam through anatomical regions of the human body. In radionuclide imaging (nuclear medicine) they are formed by acquiring photons from a body section that is within the field of view of a gamma camera. The difference is that the tomographic methods produce images of thin sections or slices through a body section. Each method has its features with respect to physical image characteristics and clinical applications. There are both values and limitations of each.

From a historical perspective the projection methods were the first, and they predominated for at least 80 years. It was the introduction of digital technology and computers beginning in the 1960s that enabled the development of the computed tomographic methods that were to revolutionize clinical imaging. The development of x-ray computed tomography (CT) was a major step in this process.

Computed tomography (CT) and the methods to follow including MRI, SPECT, and PET consist of two phases: the *acquisition* of data often referred to as scanning, and the mathematical calculation of an image from the acquired data, generally referred to as *image reconstruction.* A reconstructed image is a mathematical representation of some physical characteristic of the tissue at each point within the imaged area. With CT, X-ray attenuation is the physical characteristic. The calculated value for each point within an image (pixel) is a discrete sample and is subject to statistical error. This error appears in an image as visual noise. Developments over the years have addressed this issue resulting in more precise representations of tissue characteristics. Here our interest is specifically on x-ray computed tomography and its evolution through many steps or "generations" of development. To provide perspective we will review the technical and mathematical requirements for producing "reconstructed" tomographic images. The two distinct functions and phases, technical and mathematical, in the production of a CT image are compared in Fig. 5.

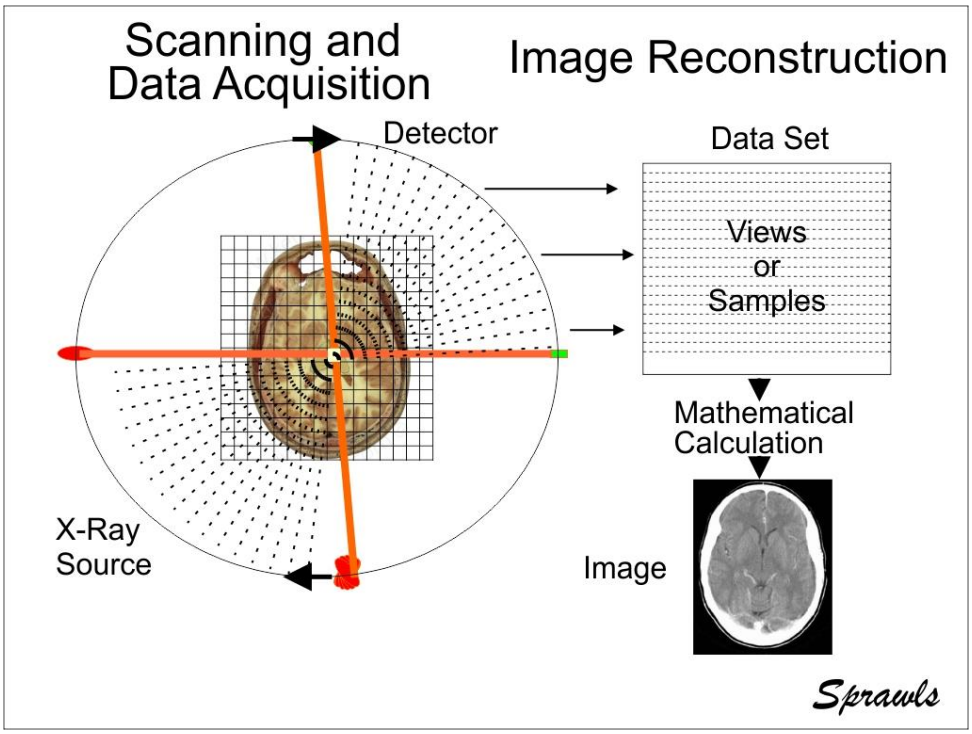


Fig.5. The two phases of CT, scanning and acquiring data that is then used to mathematically calculate, or reconstruct, an image.

The continuing developments and evolution of computed tomography over many years generally progressed along two pathways, the physics and technology for *data acquisition* and the mathematical methods for *image reconstruction*. The common goal of each is to produce high-quality images (visibility) with consideration for radiation dose to patients and as fast as possible.

It was the specific requirements for the data to be used for image reconstruction that placed demands on the technology for scanning and data acquisition. Image reconstruction requires a large set of measurements, or samples, to form each image and as described before, that is a time consuming process.

The computed tomography process requires passing an x-ray beam and collecting attenuation data through the body in the plane of the slice being imaged and then using that data to create an image of the slice. It is a two-step, or phase process.

The physical quantity being measured and displayed in the images is x-ray attenuation values. The image displays attenuation values for each voxel in the tissue slice but these cannot be measured directly. The measurements during the scanning and acquisition phase are of the total or integral attenuation along pathways through the body section as illustrated in Fig. 6.

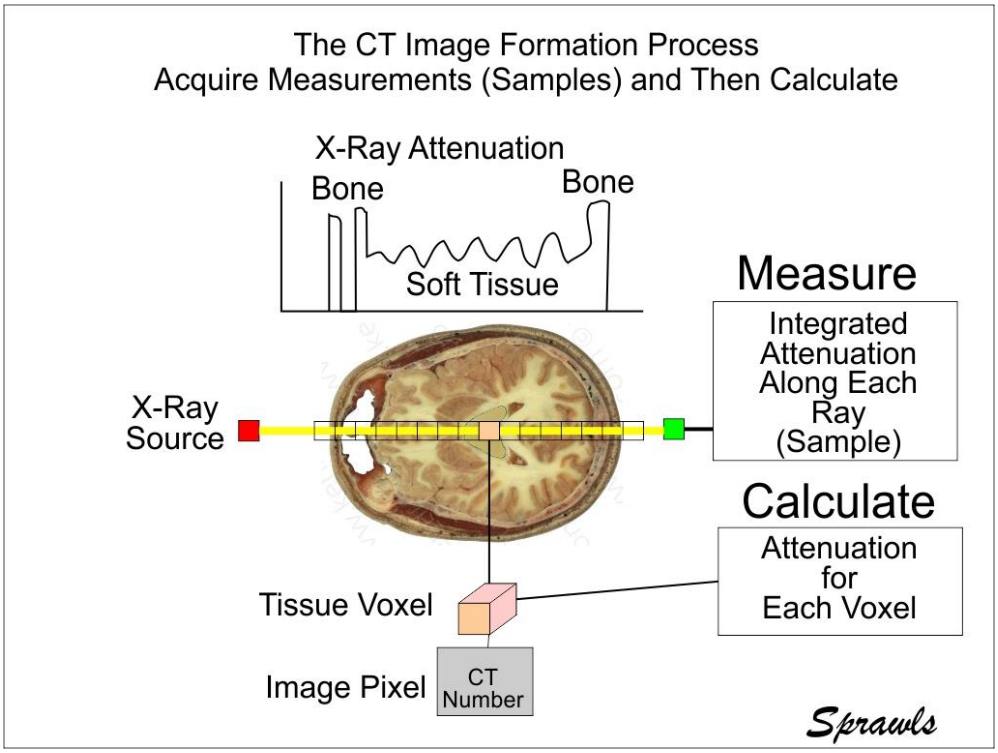


Fig. 6. The two phases in the formation of CT images, measuring and acquiring data followed by calculating attenuation values for each voxel. The illustration is for one ray through the body but many (100s) are required to produce an image.

The first challenge that had to be overcome to make computed tomography possible was developing a mathematical method for calculating attenuation values for individual voxels/pixels from measurements of total or integral attenuation along a pathway through a body section as shown. This was to become known as *image reconstruction*.

IV. MATHEMATICAL IMAGE RECONSTRUCTION

The need for imaging methods that could move beyond projection imaging and its limitations was the motivation for a variety of investigations both for medicine and other potential applications. Although some of this research was innovative and significant, apparently it did not contribute to the actual development of the CT methods and systems for medicine. Webb in *From The Watching of Shadows* provides an extensive review of these investigations. One of these was Tetelbaum S. I., About a method of obtaining volumetric images using X-ray radiation, 1957, Izvestia Kiev Polytechnic Institute, Works of the Electrotechnical Faculty, although this innovative work did not get recognized and contribute to the development of CT.

The Radon Transform

In 1917 the Austrian mathematician Johann Karl August Radon (Ref. 6) introduced the “Radon transform” which represents projected data or line integrals of functions (for example density values) in a form that could be processed with the inverse transform to reconstruct the original functions, as could be displayed in images. This is generally recognized as a significant event in the field of image reconstruction but apparently did not directly contribute to the development of the first CT methods and systems for medicine.

Cormack and Hounsfield

It was Alan Cormack and Geoffrey Hounsfield as discussed later who developed reconstruction methods independently and without knowledge of Radon’s work. In addition to developing mathematical reconstruction methods they also combined that with the technology and process for scanning and acquiring data to form tomographic representations and images. That is the origin of computed tomography for medical applications.

V. ALLAN M. CORMACK DOING THE MATH

Allan Cormack, a physicist who recognized the need for more accurate radiation attenuation characteristics within a body section for radiation therapy treatment planning, developed the method that is the foundation of computed tomography. In 1979 he and Godfrey Hounsfield jointly received the Nobel Prize in Physiology and Medicine for "for the development of computer assisted tomography."

Fig.7. Allan Cormack along with postage stamps honoring him and cover of his biography, Imaging The Elephant.

Cormack's early career can be reviewed in the BIOGRAPHY section at the end of this chapter. In 1950 he returned to South Africa from Cambridge and during this period he was asked to serve for six months as the resident medical physicist in the radiology department in Cape Town, where he supervised the use of radioisotopes as well as the calibration of film badges used to measure hospital workers' exposure to radiation. This was his introduction to medical physics. At Groote Schuur Cormack witnessed firsthand how radiation was being used in the diagnosis and treatment of cancer patients. Baffled by deficiencies in the technology used for such procedures, Cormack began a series of experiments and developments.

One of his special concerns was that treatment planning was based on a body cross-section assumed to be of homogeneous attenuation rates. This was because it was not possible to determine the actual distribution of attenuation characteristics throughout a section of a body. This was the problem his research addressed and results reported in his paper, *"Representation of a Function by its Line Integrals, with Some Radiological Applications"* published in 1963 with a follow-up in 1964. (Ref.7, 8.)

In his Nobel Lecture on December 8, 1979, *Early two-dimensional reconstruction and recent topics stemming from it,* and published in *1980* (Ref. 9) Cormack provides a comprehensive review of his activities.

He emphasized that it was a mathematical problem that was to be solved. Even after extensive search of the literature he did not learn of Radon's publication until the 1970s.

It was necessary for him to develop the mathematical reconstruction process from the beginning. Much of his lecture discussed various mathematical issues relating to the general problem, which included the effects of noise that is associated with measurement of radiation. It is interesting that his analysis gave emphasis to the potential advantages of using protons rather than x-radiation for CT imaging.

By 1963 he had constructed the apparatus shown in Fig.8 and began experiments.

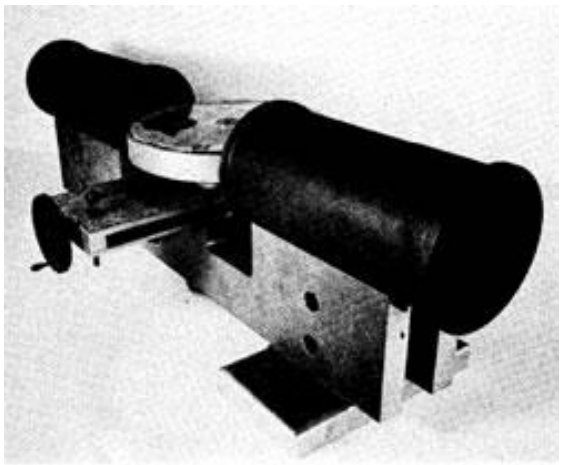


Fig. 3 (Nobel address)

Fig. 8. Cormack's experimental apparatus.

The apparatus consisted of a radioactive source in one of the black cylinders and a radiation detector in the other. A circular phantom with some embedded objects is in the center and can be rotated in increments. A diagram of the phantom is shown in Figure 8. The experiment was to make measurements of the radiation through the phantom along different directions or angles of rotation, and then mathematically calculate the attenuation characteristics along a line through the phantom. A result is shown in Fig. 9.

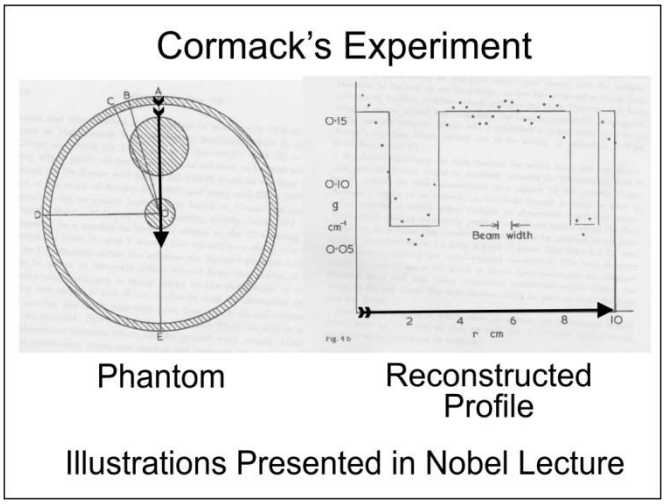


Fig. 9. Diagram of phantom scanned and reconstructed profile of attenuation along a pathway through the phantom as illustrated. The dots representing the calculated values are compared to the actual values represented by the solid line.

He reconstructed profiles along other pathways through the phantom. Although he did not combine these profiles and display as images of the phantom it was a fundamental method for producing *computed tomographic images*. He had combined the processes of scanning and measuring total radiation attenuation along pathways through the phantom and then mathematically calculating attenuation values at points within the plane of the phantom.

As discussed in his Nobel Lecture these results were published in 1963-64 (Ref.3,4) but attracted very little interest—and none from the medical imaging profession. His normal teaching and research kept him busy and he thought very little about this project until the early 1970s. That is when he first learned of Radon's publication and Hounsfield's development of the technology and process for computed tomography imaging at EMI in London.

With renewed interest his research was focused on exploring the mathematical work of others that applied to image reconstruction and investigating some of the features that would be of value in medical imaging. One of these was the capability of determining very small differences in attenuation (tissue density) within an image plane. This was to become perhaps the most significant characteristic of computed tomography imaging.

Between 1956 and 1964, most of his research in connection with the development of computerized axial tomography was conducted on his own time. Neither of his two Journal of Applied Physics papers met with significant response, despite the fact that they proved the feasibility of his method for producing images of heretofore non visible or barely visible cross sections of the human body.

VI. SIR GODFREY NEWBOLD HOUNSFIELD DEVELOPING THE TECHNOLOGY AND METHOD

The development of the first CT system for medical applications is considered as the *second giant step* toward the goal of expanded medical imaging capabilities. It is significant to recognize that this along with Roentgen's *first giant step* were both recipients of Nobel Prizes. It was Godfrey Hounsfield who developed the first computed tomography system and method producing one of the first clinical images shown in Fig. 10.

Fig. 10. Godfrey Hounsfield and a first clinical image showing the tissues and a tumor within the skull.

Hounsfield's early career can be reviewed in the BIOGRAPHY section at the end of this chapter. This includes biographical information presented and published associated with awarding of the Nobel Prize and provides insight into his early life and the factors contributing to his distinguished career as an engineer and innovator. (Ref.10.)

From His Autobiography

I joined the staff of EMI in Middlesex in 1951, where I worked for a while on radar and guided weapons and later ran a small design laboratory. During this time I became particularly interested in computers, which were then in their infancy.

[After one of his projects was abandoned] … rather than being immediately assigned to another task I was given the opportunity to go away quietly and think of other areas of research which I thought might be fruitful. One of the suggestions I put forward was connected with automatic pattern recognition and it was while exploring various aspects of pattern recognition and their potential, in 1967, that the idea occurred to me which was eventually to become the EMI-Scanner and the technique of computed tomography.

The steps in my work between this initial idea and its realization in the first clinical brain-scanner have already been well documented. As might be expected, the programme involved many frustrations, occasional awareness of achievement when particular technical hurdles were overcome, and some amusing incidents, not least the experiences of travelling across London by public transport carrying bullock's brains for use in evaluation of an experimental scanner rig in the Laboratories. The experimental system Hounsfield used for developing the process is shown in Fig. 11.

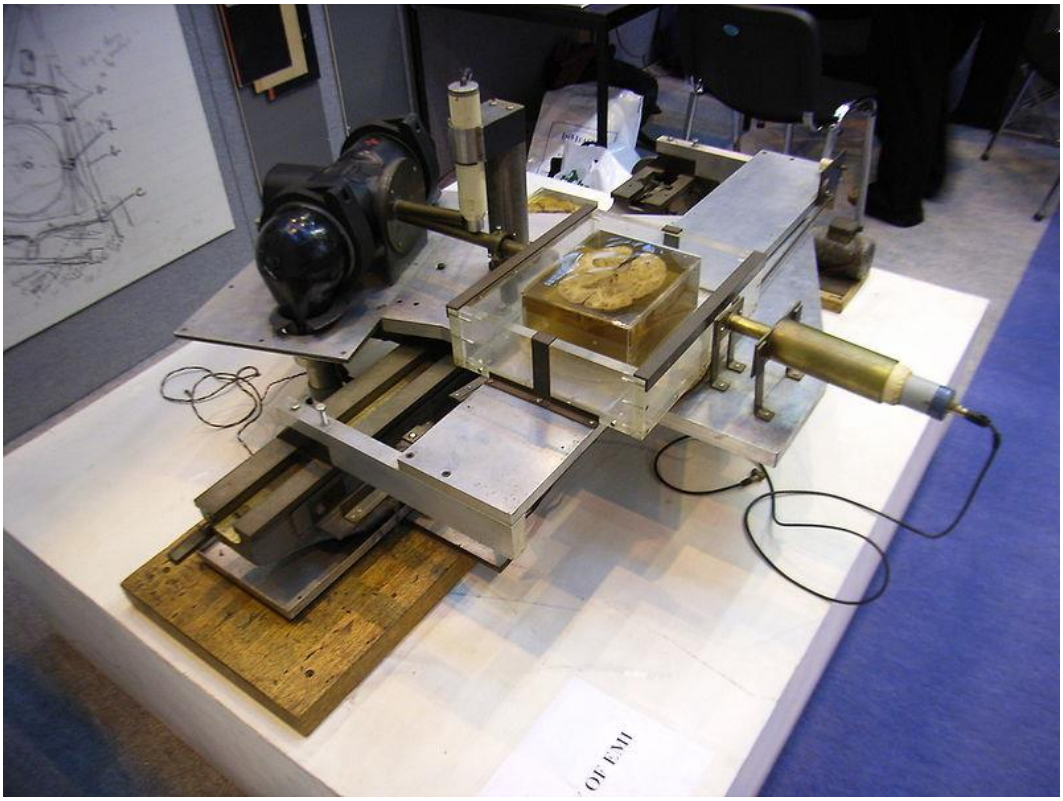


Fig. 11. Hounsfield's laboratory device used in the development of the computed tomography method.

After the initial experimental work, the designing and building of four original clinical prototypes and the development of five progressively more sophisticated prototypes of brain and whole body scanner (three of which went into production) kept me fully occupied until 1976. Since then I have been able to broaden my interest in a number of projects which are currently in hand in the Laboratories, including further possible advances in CT technology and in related fields of diagnostic imaging, such as nuclear magnetic resonance.

VII. THE FIRST CLINICAL COMPUTED TOMOGRAPHY AND BEGINNING OF A REVOLUTION

Hounsfield's work leading to the development of the first CT system for clinical applications and the immediate demonstration of its capabilities for imaging the soft tissues of the brain within the skull along with its high sensitivity for showing contrast among the tissues, especially between normal and pathologic, is clearly the foundation of modern medical imaging. A description of his system and imaging method, along with some clinical results, was published in 1973 (Ref.7, 8).

It is significant that he developed both the *technology* for scanning to collect data on x-ray attenuation through a body section and a *mathematical* method for image reconstruction--the two major phases of computed tomography. His diagram of the scanning process is illustrated in Fig. 12.

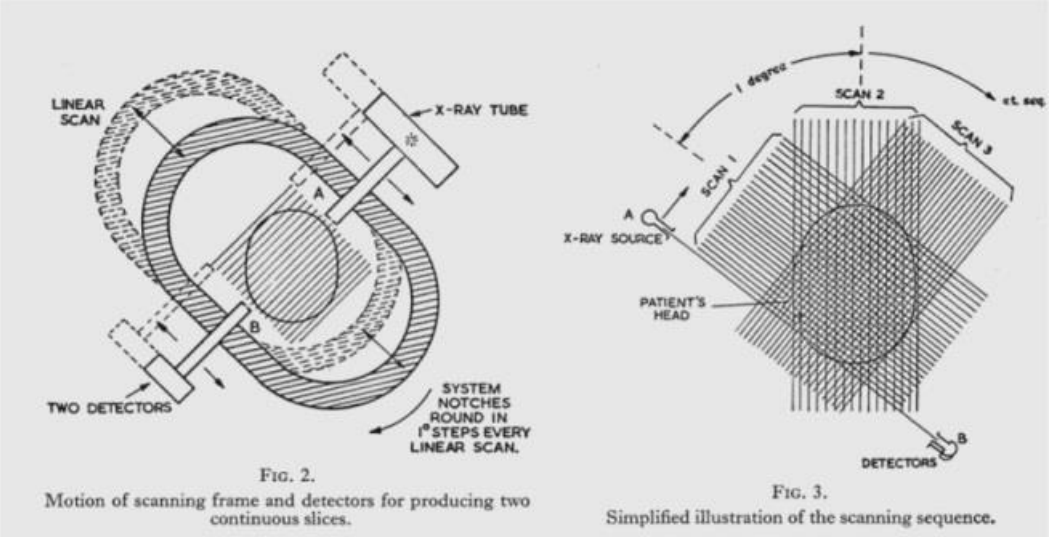


FIG. 2.
Motion of scanning frame and detectors for producing two continuous slices.

FIG. 3.
Simplified illustration of the scanning sequence.

Figure 12. Hounsfield's diagram of the scanning process for his first CT system used for clinical imaging.

This is of major historical significance from two perspectives. First, it illustrates the high level of creativity and design by Hounsfield to solve a complex problem of measuring x-ray attenuation through multiple pathways through a body section that could then be used for image reconstruction. Second, it provides the foundation and reference point for the many developments in CT technology that was to continue over at least the next half-century.

Characteristics of Hounsfield's Scanner

The scanning process for Hounsfield's first-generation scanner as illustrated in Fig. 12 was the "scan-rotate" method. A relatively small "pencil" x-ray beam was projected through the patient's body and recorded by a single detector. The x-ray tube and detector were mounted and moved together during the scanning process. The x-ray tube and detector assembly would be rotated around the patient in one degree increments for 180 positions or "views." In each angular position the x-ray beam would then be scanned across making 160 measurements. This would provide a total of 28,800 data points that would later be used to reconstruct one image. A typical scan time for one image was approximately 4.5 minutes.

As described by Hounsfield, each beam path forms one of a series of 28,800 simultaneous equations in which there are 6,400 variables. If there are more equations than variables they can be solved to provide values for each cube in the slice (voxel). The picture is built up in the form of a 60 by 60 matrix with the value in each point representing the absorption coefficient of the material in the corresponding volume of material in the slice. After appropriate scaling the absolute value of the absorption coefficient for the various tissues is calculated to an accuracy of ½ %.

For the early scanners the images were displayed on a CRT and photographed with a Polaroid camera for clinical viewing or the digital values could be printed out as shown in Fig. 13. It is the Author's recollection that the digital printouts were interesting but of little practical value.

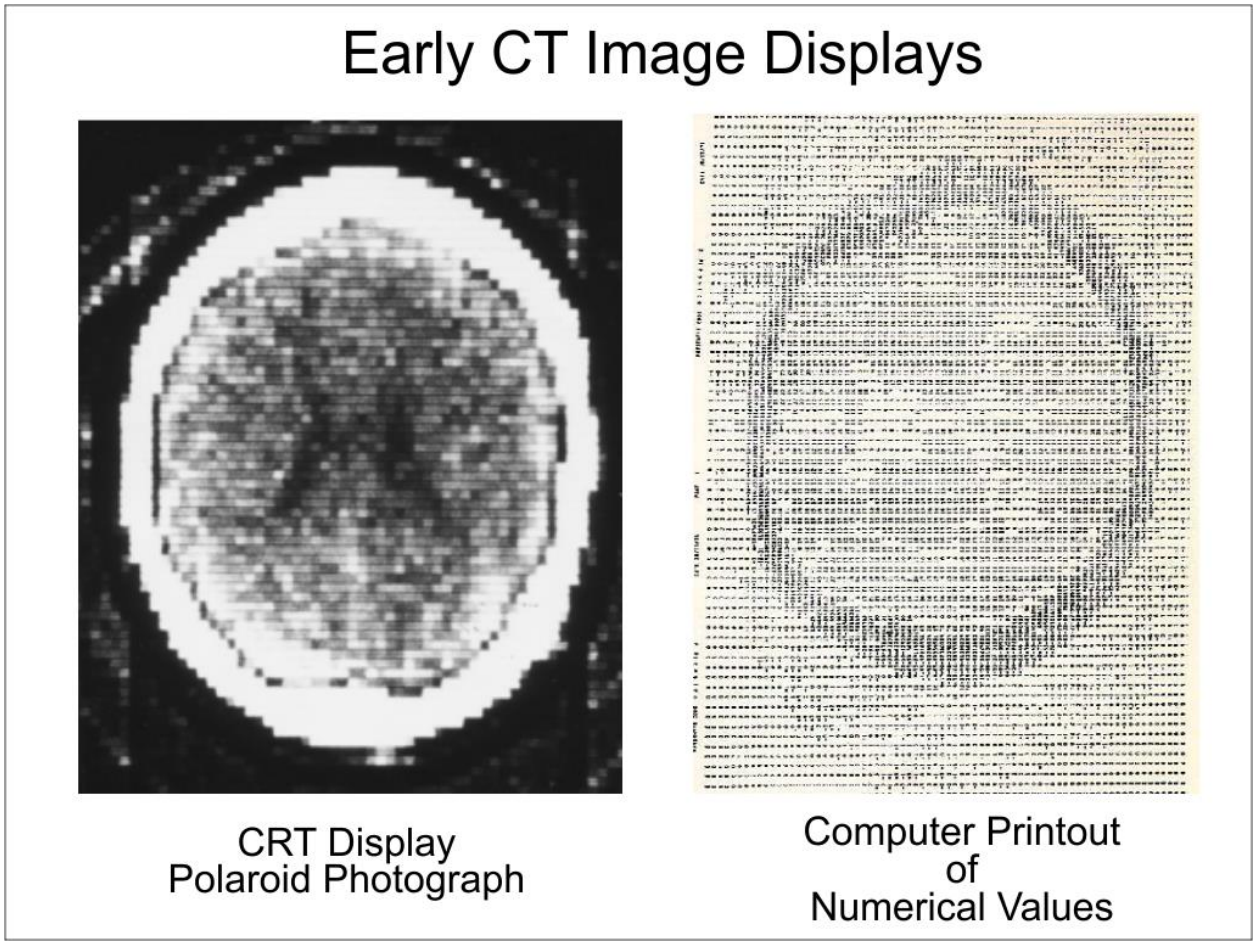


Fig.13. The two types of image displays for the first CT scanners.

Numerical Values for Tissues

There were two major features of computed tomography as developed by Hounsfield that were to revolutionize medical imaging and clinical medicine. One, as discussed above, was the formation of truly tomographic images. This was the ability to produce images up close and within a very short distance (a few millimeters) of an anatomical location and without interference from the overlying and surrounding anatomy, especially the dense skull. This was a significant "two-dimensional" *geometric characteristic*.

The other factor that can be considered as the "third dimension" or "numerical depth" of the image is the characteristic that was a major revolution in medical imaging. That was calculating a numerical value for each tissue that was determined from the x-ray attenuation measurements. For this Hounsfield used two scales, both expressing tissue attenuation values in relationship to that of water. These are compared in his diagram shown in Fig. 14.

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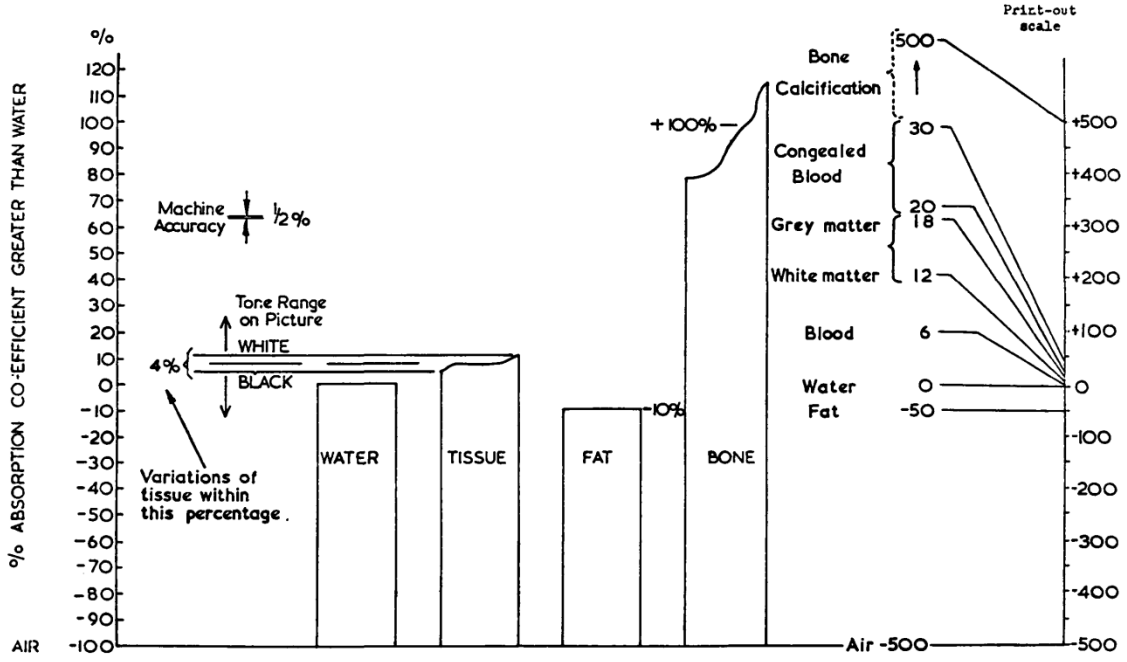

FIG. 9.

Illustration of machine sensitivity. The scale on the right is an arbitrary scale used on the print-out and is related to water = 0, air = 500 units. It can be seen that most materials to be detected fall within 20 units above zero and can be covered by the adjustable 4 per cent "window".

Fig. 14. Hounsfield's diagram published in Ref. 11 that illustrates many of the features of the CT method.

The scale on the left shows the tissue attenuation as percentage values compared to water. The scale on the right displays numbers calculated from attenuation coefficient values with water assigned a value of zero and air a value of -500. These were known as CT numbers and expressed in *Hounsfield units* on the scale that he developed as shown in Fig. 14.

These numbers could be printed out as shown in Fig. 13. The scale was later changed with air assigned a value of -1000. This provided an expanded scale with a wider range that was especially useful at the upper end for the larger range of densities and attenuation values of bone.

In this diagram Hounsfield illustrates several major and valuable characteristics of the CT process. This is made possible by having images in a digital form that can be computer processed to selectively enhance visibility of specific tissue characteristics, especially abnormal or pathologic conditions.

Contrast Sensitivity

In comparison to radiography, CT has a very high *contrast sensitivity* or ability to produce visible images among tissues that have very little physical contrast based on differences in physical density. As illustrated the various soft tissues produce numerical values that are sufficiently different and a source of contrast that can be displayed in an image.

Windowing

Windowing is the specific feature of CT that makes possible the high contrast sensitivity and ability to see the contrast among the soft tissues. One of the advantages of capturing or reconstructing images in a digital form (rather than on analog film) is the ability to record a wide range of x-ray attenuation measurements ranging from bone to air. The soft tissues are

confined to a very small range in between. Hounsfield shows this as 4% of the total range. If this "raw" image is displayed there would be visible contrast between bone and air but little or none among the soft tissues. Windowing is the process of selecting the small range of numbers representing the low physical contrast among the soft tissues and displaying with high visual contrast using the full image brightness "tone range" from black to white as illustrated in Fig.14. Windowing was to become one of the highly valuable features of the various digital imaging methods. Most digital imaging methods have a wide dynamic range and can record a wide range of data, signals, or radiation exposures acquired from a patient's body during an imaging procedure. This is very different from film used in radiography that has a very narrow dynamic range or latitude. Windowing is used to select a small range of data from the wide acquired range and display it with high visual contrast. The success of CT to produce visual contrast among soft tissues, as in the brain, depended on the ability to window.

VIII.THE EARLY EMI SCANNERS AND CLINICAL APPLICATIONS

In 1971 the prototype scanner was installed at Atkinson Morley Hospital in London and used by James Ambrose, MD who presented a report on the examination and findings for 70 patients in 1972 and publishes in 1973 (Ref.13). In the summer of 1972, EMI launched Hounsfield and Ambrose on a lecture tour of the United Kingdom and United States. Five scanners were preordered, with expected delivery in 1973. By June 1974, EMI had sold 35 scanners in the United States alone.

The one installed in the Author's institution, Emory University in Atlanta, is shown in Fig. 15.

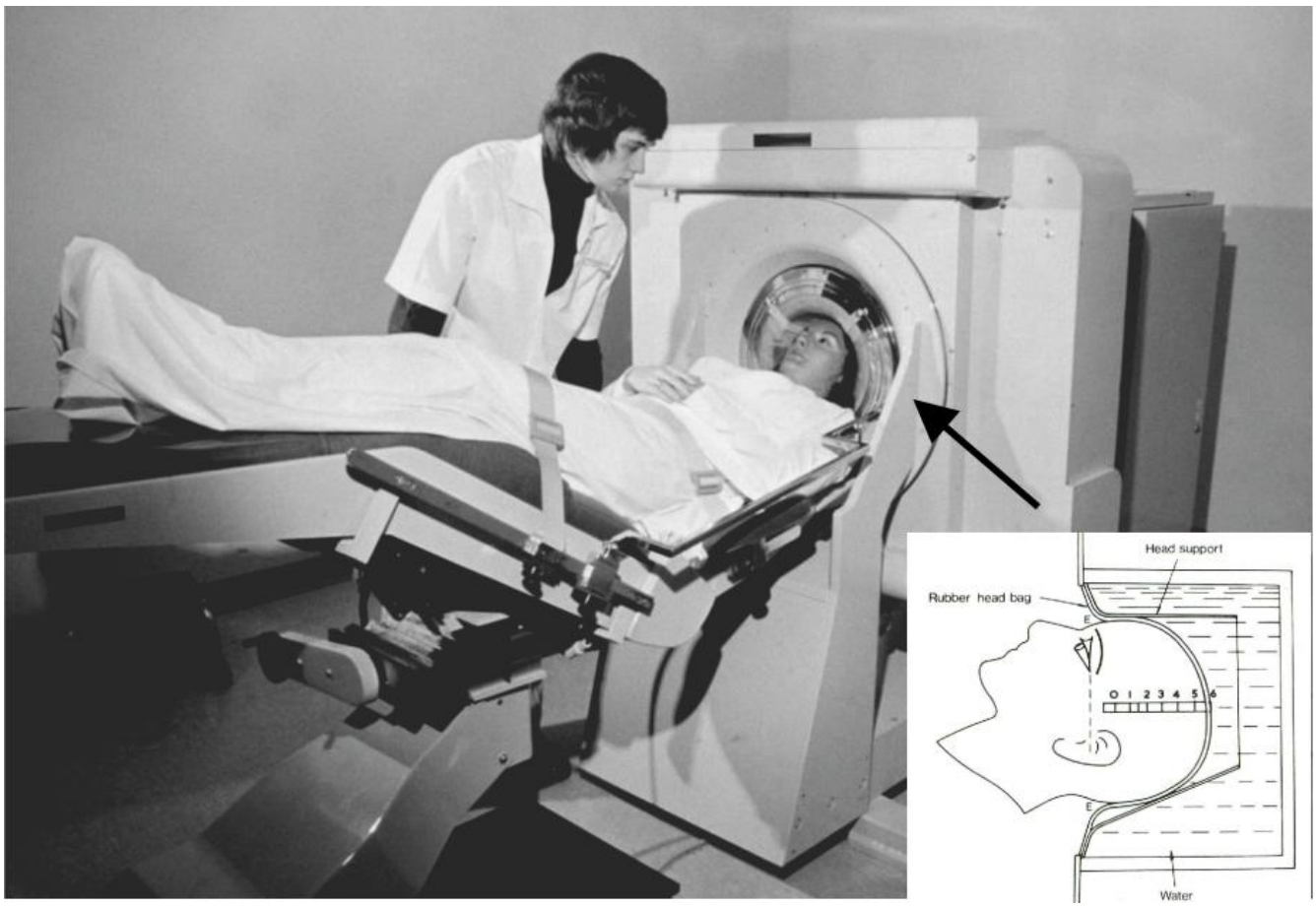

Fig. 15. Technologist preparing a patient for scanning with an early EMI system.

Here we will use it as an example of the early scanners to explore some of the design features and operational details.

It was a head-only scanner and the patient's head was tightly surrounded by a water-filled bag. The major purpose of the water bag was to reduce the wide range of x-ray beam attenuation and exposure to the detectors from air outside of the head to the thickest part of the skull.

Because of the long scan times (approximately four minutes per slice) patient motion was a problem and strong restraining belts were required. On a later scanner the Author installed additional automobile seatbelts because of the motion problem.

As the medical physicist working with this first scanner the concerns were generally mechanical issues, image artifacts, and calibrating the relation of CT numbers to material densities. For this we designed and constructed our own phantoms and test objects.

The Scientific, Technical, and Medical Impact of the Hounsfield CT System

Hounsfield's development of computed tomography (CT) revolutionized and made a rapid impact on clinical medicine because of the synergistic combination of several significant factors.

A major scientific contribution was establishing numerical values relating to physical characteristics of tissues in the body with a high level of sensitivity for distinguishing among the different tissues. This made possible the production of images with high contrast sensitivity. It was the combination of this with the scientific and mathematical method of image reconstruction that was the foundation of computed tomography.

Hounsfield's engineering and development of the technology was a major contribution. The innovative mechanical design to produce and collect the attenuation data that was required for image formation by a reconstruction process provided a solution to a complex problem with many factors that had to be considered. In addition to its immediate impact it provided future scientists and engineers with considerable insight into design characteristics that would be used in the development of CT systems by many manufacturers.

A major factor contributing to its rapid impact was Hounsfield's early and continuing collaboration with physicians, especially Dr. Ambrose. In the early stages of his research on producing images of objects that were enclosed and hidden in some structure the thought of the human body came up. Discussions with some medical professionals confirmed a need and focused attention to the human head with the brain hidden within the skull and not visible with any other imaging methods available at that time. As the system was developed and the first prototype installed in a hospital the medical staff identified applications, demonstrated its value, and publicized and promoted this as a major medical breakthrough.

The foundation was established, and it was on to the future.

IX. ROBERT LEDLEY AND THE WHOLE BODY CT

A next major step in expanding the clinical value and range of anatomical regions that could be imaged was the development of the whole body scanner.

The head-only CT as developed by Hounsfield was a major contribution to the field of medicine in several respects. The ability to produce tomographic images displaying visible contrast among soft tissues was the breakthrough. It was imaging the previously invisible brain within the dense skull that made the immediate impact. Even though other parts of the body were being imaged with conventional radiography and fluoroscopy and especially enhanced with the use of barium and iodine-based contrast media, potential applications of CT were becoming apparent. The transition from a head-only to a full-body imaging system would require a major redesign for scanning and acquiring the data. This was to be the contribution of Dr. Robert S. Ledley shown along with the first whole body scanner in Fig. 16.

Fig. 16. Dr. Ledley with the ACTA scanner in 1974.

The early career of Dr. Ledley can be reviewed in the BIOGRAPHY section at the end of this chapter. He began his work on CT scanning in 1973. He assembled a group at Georgetown to build the Automatic Computerized Transverse Axial, or ACTA, scanner, which could scan the entire body. In 1974 he established the Digital Information Science Corporation (DISC), selling the machines for $300,000 each. After obtaining the patent for the ACTA scanner, he sold his company to Pfizer Medical Systems Company. The CT division was later purchased by some of the larger and established medical imaging equipment manufacturers.

What was becoming apparent in the industry was that the companies where the two major CT systems were invented and developed (EMI and DISC) did not have the medical imaging capability; manufacturing, marketing, and service support to survive in the CT business.

Dr. Ledley was inducted into the National Inventors Hall of Fame in 1990 and awarded the National Medal of Technology and Innovation by President Bill Clinton in 1997. The original prototype of the ACTA scanner is at the Smithsonian Institution in Washington.

X. THE CONTINUING DEVELOPMENT AND EVOLUTION OF COMPUTED TOMOGRAPHY

The early systems developed by pioneers especially Hounsfield and Ledley introduced and established CT as a revolutionary clinical diagnostic method. This was to be the foundation for many years of research and development to expand the capabilities and desirable characteristics of computed tomography. Much of this involved development in technology, especially electronics and digital imaging and computer technology.

What was to follow is a continuing series of developments, *each a step* toward the goal of increasing the capabilities and values of computed tomography as a major medical procedure.

Every year at major medical conferences including the Radiological Society of North America (RSNA) new advances in technology were introduced by the industry and updates on clinical imaging were presented by the medical professionals. Often the clinical presentations were demonstrating the innovations and capabilities of the technology.

It has become the practice to organize the evolution of computed tomography into “generations” each distinguished by specific design or functional characteristics. Each generation provided another step to the goal of increased visibility and especially faster scanning and data acquisition. Throughout the evolution of CT through the several generations it was the

time required to produce an image that was the major challenge. Developments resulted in the reduction of time to produce one image from approximately four (4) minutes to seconds. For many years and encompassing the first five generations the scanning and data acquisition was limited to one image at a time. A major evolution was developments in detector technology along with innovations in data acquisition scanning and reconstruction methods that made possible the simultaneous data for multiple image slices and three-dimensional (3D) volumes.

We will first consider the developments within the first five "single-slice" generations followed by the evolution of detectors and the additional generations.

The Single-Slice Scanner Generations

Hounsfield's design and systems manufactured and distributed by EMI introduced CT to the world and established it as a major method for medical diagnosis. What were to follow were many additional innovations and designs to enhance performance. This was driven by three major objectives:

- To reduce the time required to produce images.
- To increase visibility of anatomical structures and signs of pathology
- To reduce and manage radiation dose to patients

The continuing series of designs especially related to the scanning process are classified into generations. A specific generation was generally characterized by the combination of x-ray beam shapes and scanning motions. Those are the geometric characteristics. Before looking at the special features of each generation let's review the general process and technical requirements for data acquisition that apply to all generations and illustrated in Figure 17.

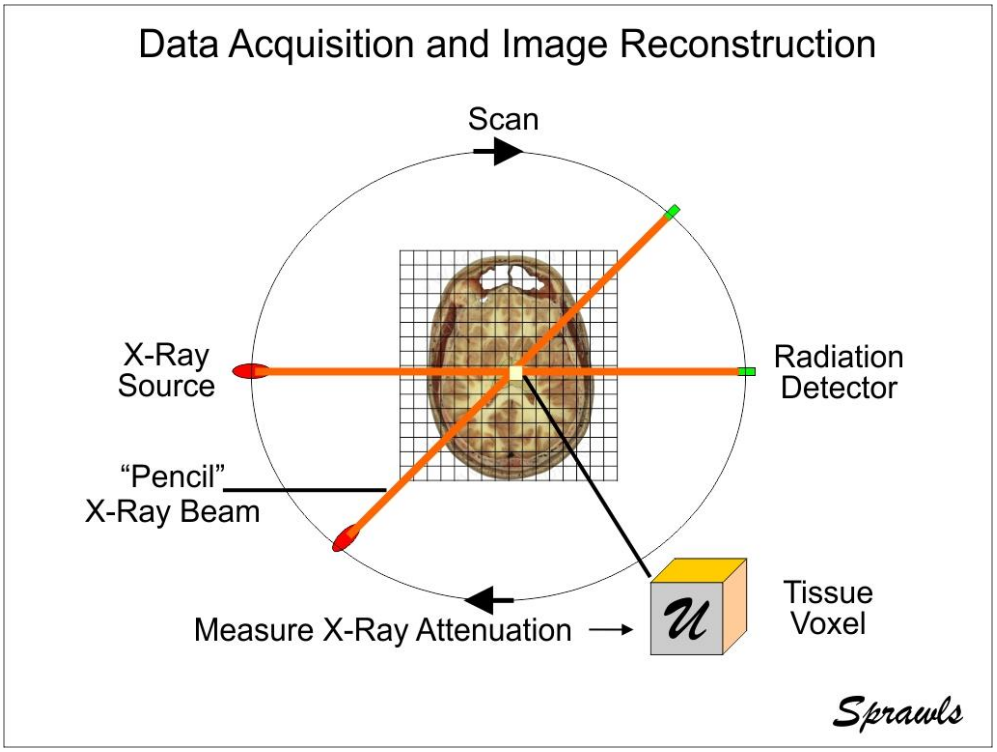

Figure 17. The objective of data acquisition by scanning and mathematical reconstruction is to determine the x-ray attenuation values for each individual tissue voxel within the imaged slice.

The first of two major phases in the formation of a CT image is the *physical or technical* scanning and acquisition of data that can then be used in the *mathematical* image reconstruction process. The number of measurements or samples required in the acquisition to form one image depends on the physical quality characteristics of the image.

The image is formed as a matrix of tissue voxels with an x-ray attenuation value determined for each. The size of each voxel is a major factor in several image quality characteristics, especially detail and noise, and should be taken into consideration in the production of a CT image. The size of each voxel within the tissue slice and corresponding pixel size within the image is determined by the matrix dimension (number of voxels/pixels) for a specific anatomical field of view. For the reconstruction process the matrix size (number of voxels) is a factor that determines the number of measurements that are required in the acquisition process. The number of required measurements is a factor determining the time to produce an image. The early experiments by both Cormack and Hounsfield used a single beam of radiation that was manually rotated around the object step-by-step. This was a very slow process that demonstrated the principle of computed tomography (CT) but not practical for clinical imaging.

The development that made clinical imaging possible was the mechanical *scanning* of the x-ray source and detectors around the patient's body. This established "CT scans" as the common name for the imaging procedure. It was the scanning function that was to be the focus of continuing research and development and evolution of the CT imaging for years to come with the different designs defining the series of generations. The design of a specific generation generally depended on the development of related technologies, especially radiation detectors.

First Generation

The system designed by Hounsfield and produced by EMI was the first generation. Some of the features have been described previously but more details of the scanning process are illustrated in Figure 18.

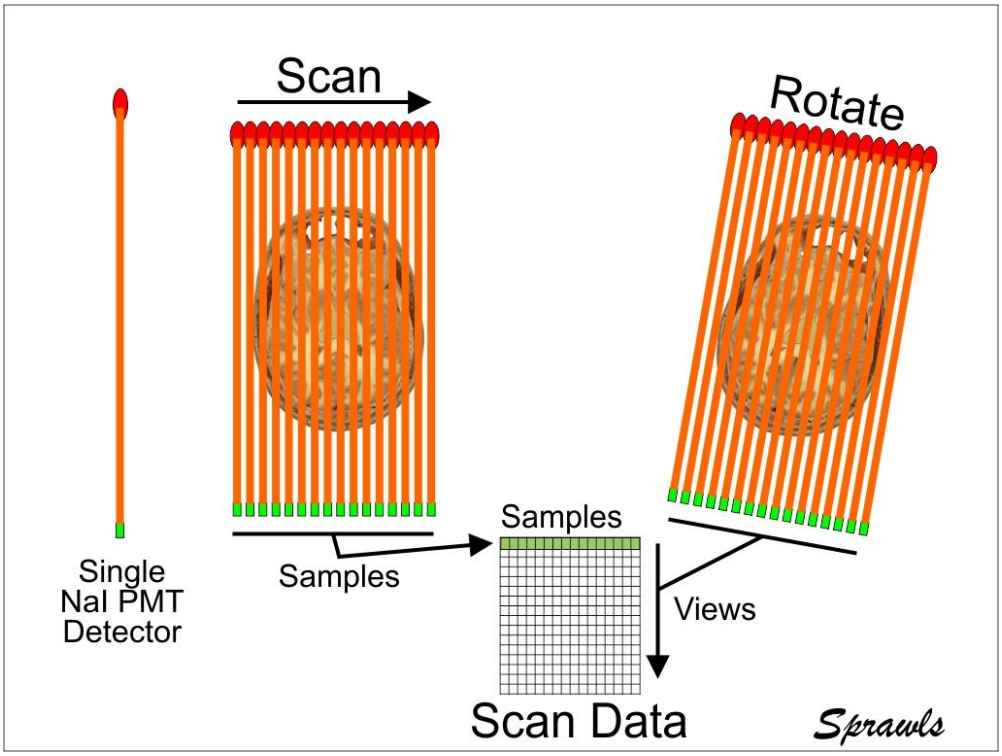

Figure 18. The scanning geometry for the first-generation CT scanner.

The limiting factor with the first-generation technology was only one detector in the image plane recording one measurement (sample) at a time. The scan data to reconstruct an image was acquired with a combination of two motions. First, the single beam was scanned across the patient making individual measurements along the way to make up one *view*. The tube and detector was then rotated about one degree for the next scan to develop the next view. A typical scan time per image was approximately four (4) minutes. This was to produce images with a 60 x 60 matrix compared to the 512 x 512 that became typical for future generations. A major goal of future generations was to produce higher quality images (smaller voxels) combined with faster acquisitions.

Second Generation

The second generation introduced the design feature that was to drive and apply to all future generations by using an array of multiple detectors in the image plane as illustrated in Figure 19.

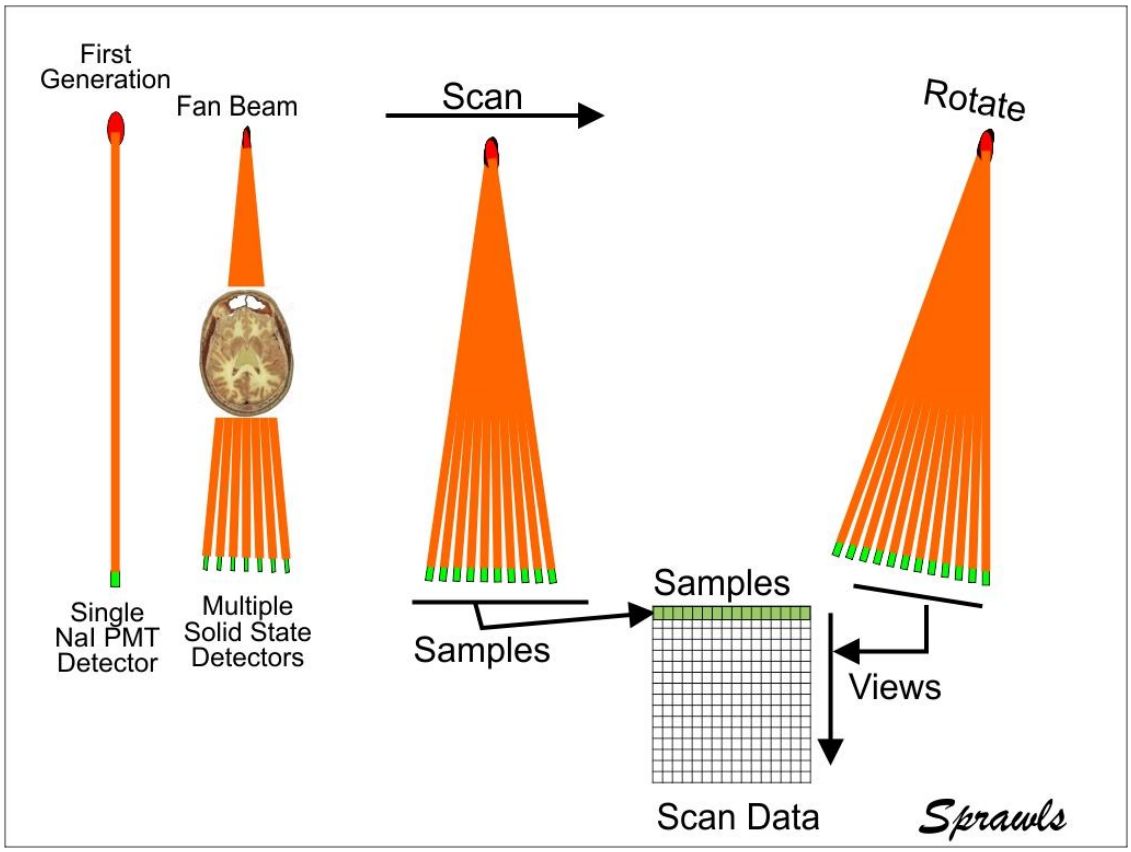

Figure 19. The geometry of the second-generation technology using an array of multiple detectors.

With an array of several side-by-side detectors and a wider fan- shaped x-ray beam more measurements or samples can be made simultaneously increasing the acquisition speed for an image. The fan beam did not have the width to cover the body section so it was necessary to scan as in the first generation. However, the scanning was in larger steps and produced a view faster.

Third Generation

The development of larger detector arrays with a fan beam that could cover a full body section made it possible to acquire a complete view from each x-ray tube location as illustrated in Figure 20.

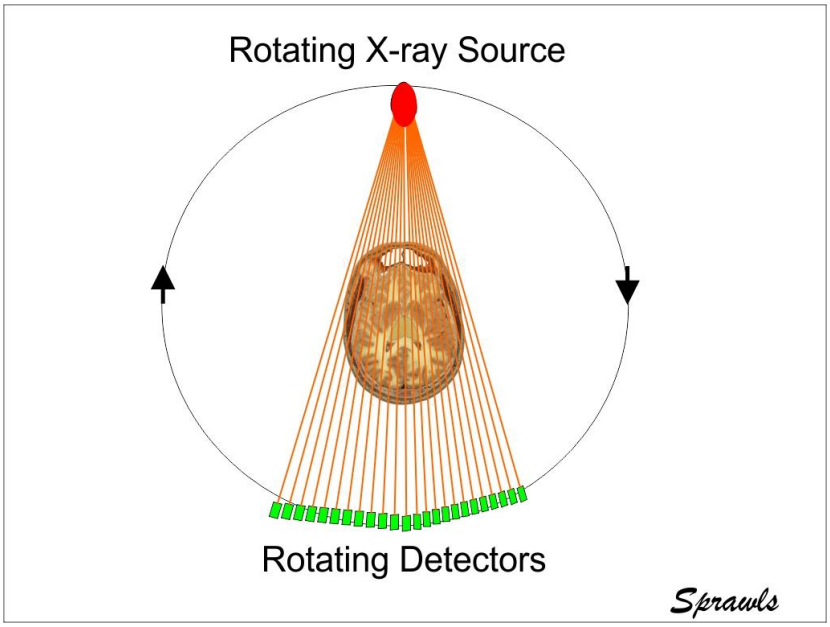

Figure 20. The rotate-rotate design that acquired a complete view from each x-ray tube location.

The technology that made this possible was the development of detector arrays consisting of many small detectors.

Fourth Generation

A next step in detector development was a stationary array that completely encircled the patient's body as illustrated in Figure 21.

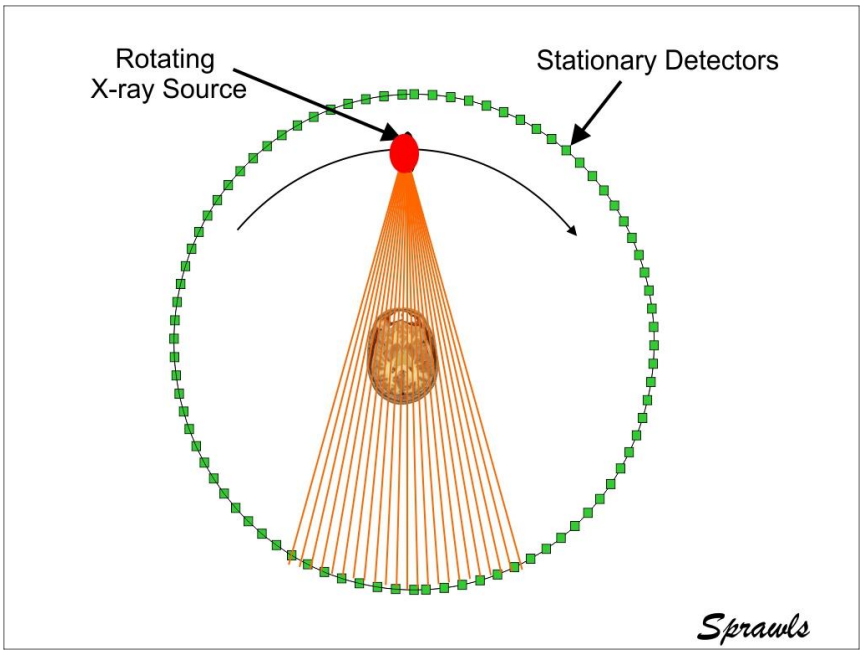

Figure 21. A large circular array of detectors that does not need to be moved.

Fifth Generation

The generally recognized fifth generation introduced a major evolution in CT design by scanning with no physical movement and much faster image acquisition. It used a scanning electron beam as illustrated in Figure 22.

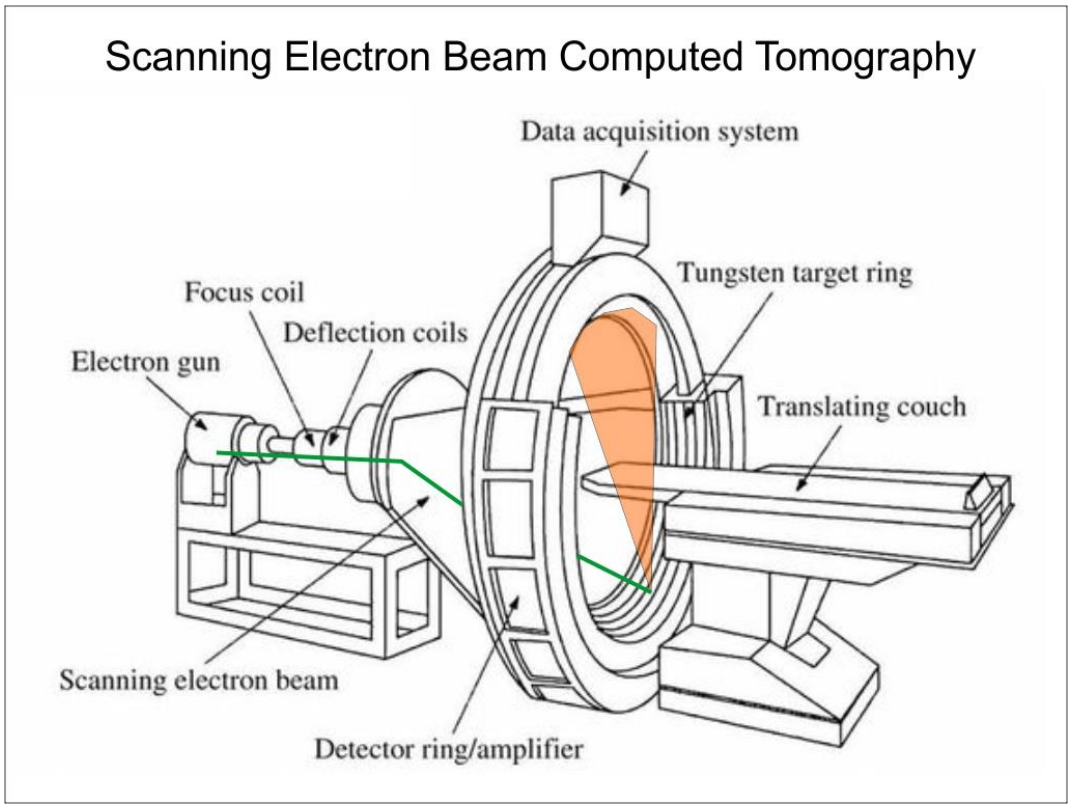

Figure 22. The scanning electron beam design that provides rapid scanning.

This method was developed by Dr. Douglas P. Boyd and other researchers from the UCSF Department of Radiology. Along with the Emerson Radio Corporation they established Imatron Associates and the scanner was known by that name. Its major clinical application was cardiac imaging to detect calcifications within the coronary arteries to evaluate the risk of heart disease.

The unique feature was a very large "x-ray tube" with an electron gun on one end and a very large semi-circular tungsten target serving as the anode on the other end. This was all enclosed in a large vacuum structure. The highly focused electron beam was scanned along the surface of the tungsten anode at a very high rate, up to 17 images per second.

This scanner enhanced the development of cardiac imaging and was generally located in research institutions. Because of its limitations in imaging most other sections of the body and organ systems it was generally not practical for most medical imaging facilities. As the more conventional CT systems were developed with the capability for cardiac imaging the unique value and role of the IMATRON system diminished. The other systems could perform a complete range of clinical procedures, including cardiac.

XI. THE DEVELOPMENT AND EVOLUTION OF DETECTORS

The detectors were the components of CT systems that established design characteristics and imaging capabilities with respect to functionality, image quality and acquisition speeds. This has evolved from essentially a single detector used by Hounsfield to multiple detectors in many different configurations. As previously illustrated it was the number and configuration of the detectors that defined the different generations.

The evolution of detectors has involved a combination of two major characteristics: materials and geometric characteristics of the individual detector elements, both in size and arrangements within arrays. For faster high-quality image acquisition the need was for large arrays of small individual detector elements. The requirements for the individual detector elements included high x-ray attenuation and conversion efficiency, low noise, and uniformity sensitivity among elements. This was to be a continuing challenge as the different detector technologies were developed and evolved. This was to include two major types of detectors with respect to materials, gaseous and solid, as illustrated in Figure 23.

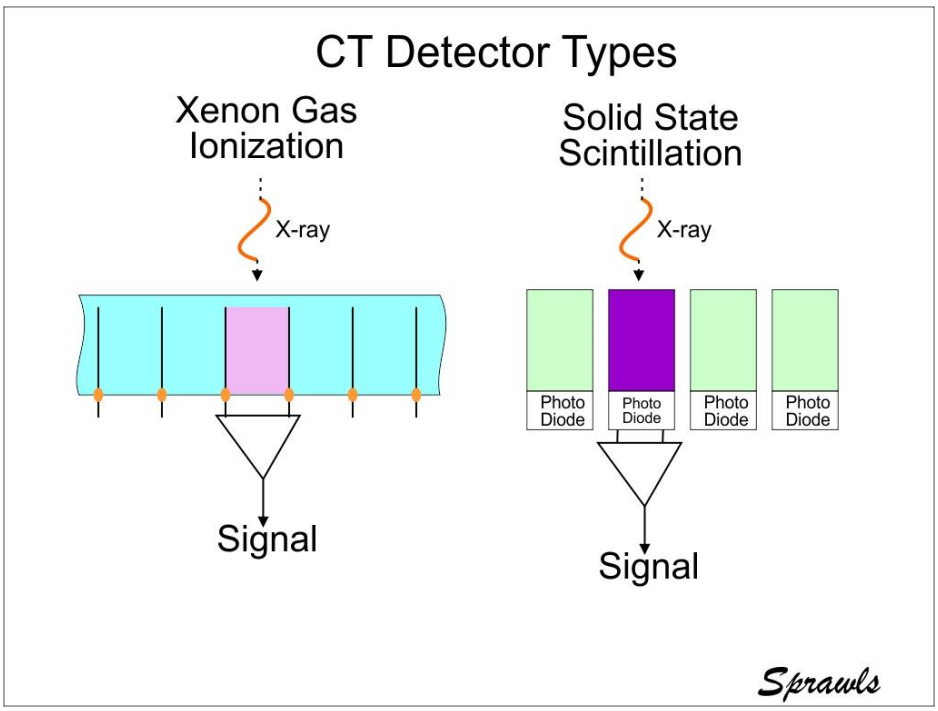

Figure 23. A comparison of the two detector types.

Each type of detector had desirable features that contributed to its value in advancing scanning performance.

Xenon Gas Detectors

A design that fulfilled these requirements with available technology was an array of small ionization chambers filled with xenon gas. This was constructed with the individual elements separated within a common enclosure capable of withstanding very high pressure. Xenon pressures up to around 25 atm were used to enhance x-ray attenuation. A value of this design was uniformity in sensitivity among elements because they shared the same gas pressure. Xenon detectors contributed to the advancement of third-generation CT systems, but their somewhat limited x-ray attenuation resulted in the transition to solid state detectors for all future applications as the solid state technology and electronics developed. Also, solid state units were more suitable than gas for construction of multiple row detector arrays that were to become the future of CT.

Solid State Detectors

A major advantage of solid-state over gaseous detectors is higher x-ray attenuation resulting in greater sensitivity. This improves the image quality to patient radiation dose relationship. A major challenge in the development of solid state detector systems was producing small detector elements with uniformity of sensitivity among the elements. With solid state each element is independent, unlike the gaseous detectors that shared common pressure. Solid state detector technology developed and evolved with the scintillation based detectors becoming a significant contribution.

It was the development of solid state detector arrays consisting of small individual detector elements that was to bring one of the major revolutions in CT: the transition from single-slice to multiple-slice acquisition, and beyond.

Multi-row Detectors and Multi-slice Imaging

Arrays of both solid state and xenon detectors used with fan beams was the enabling technology for the third, fourth, and fifth generation scanners and provided significantly faster acquisitions with respect to the earlier generations.

The next major advancement was the development of detector arrays consisting of *multiple rows* of detector elements as illustrated in Fig.24.

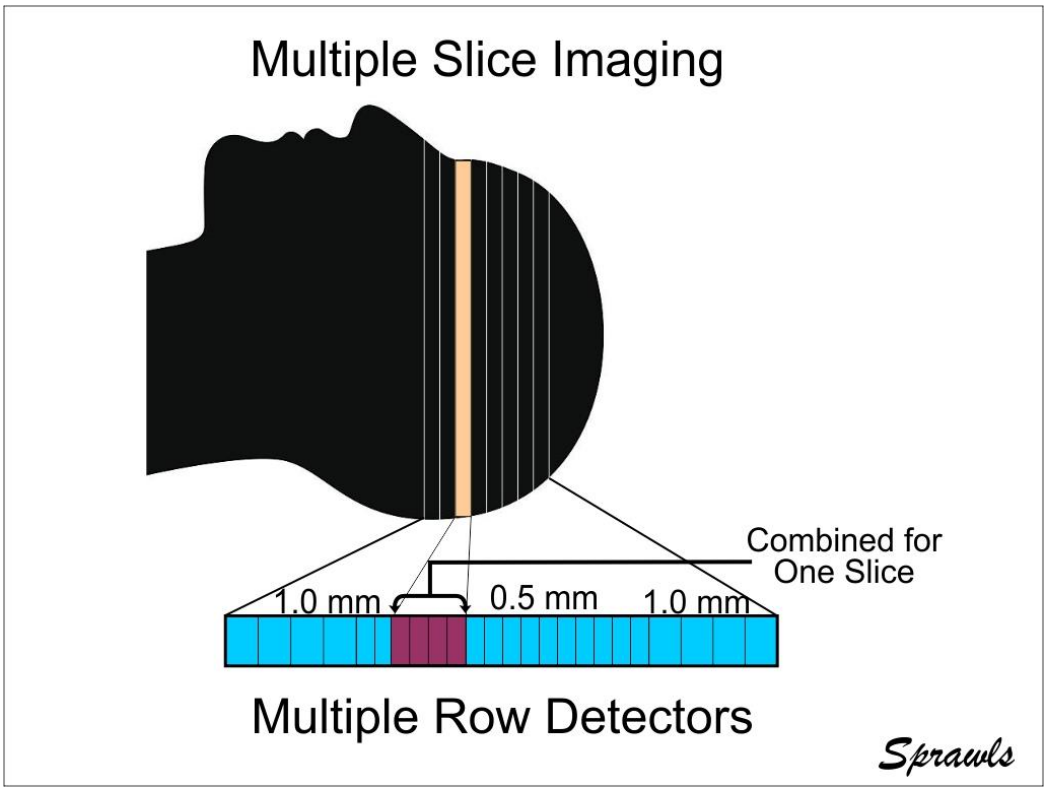

Fig. 24. Multiple Row Detectors and Multiple Slice Imaging

The immediate advantage was the ability to scan and acquire data for several or multiple slices simultaneously. This provided a significant reduction in acquisition time for a procedure. The various manufacturers had slightly different designs with respect to size and number of detectors, in general similar to that shown in figure 24. The number of rows in the designs ranged up to 64. Some designs included smaller detectors in the center that could be selected to produce thinner slices and increased image detail.

Adaptive Arrays
A valuable feature of multiple row detectors was the ability to electronically select and combine several detectors for each slice. This provided the opportunity to adjust and optimize slice thickness for specific clinical procedures.

XII. SPIRAL AND HELICAL SCANNING

One of the major steps and evolutionary events in computed tomography was the invention and development of spiral or helical scanning by Willi Kalender, introduced at the RSNA 1n 1989. Dr. Kalender, Fig. 25, was a major contributor to the development of computed tomography physics and technology throughout his career.

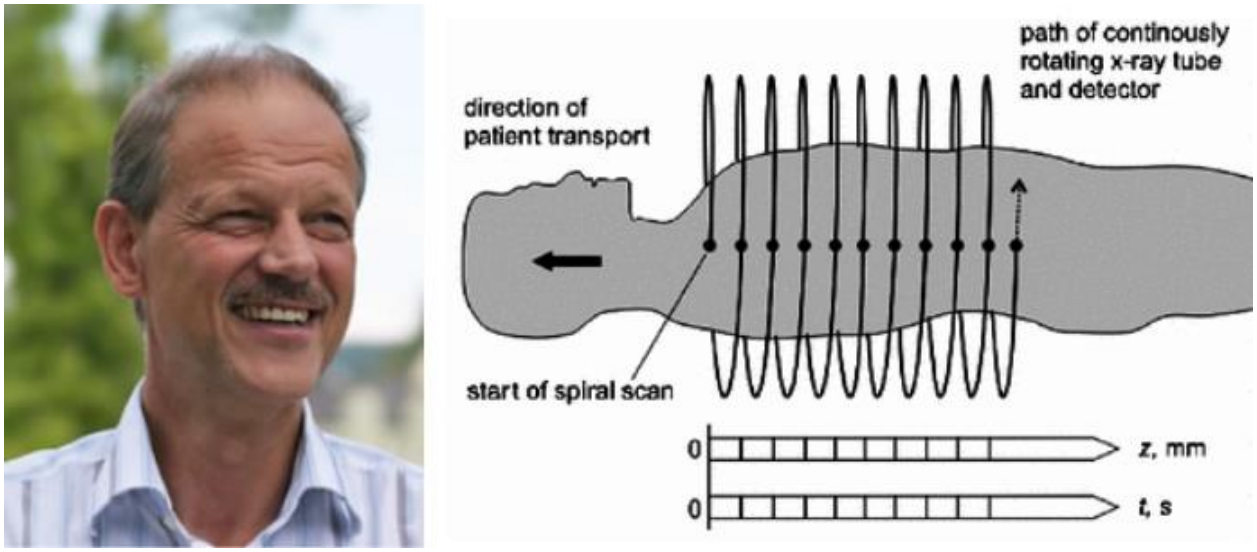

Fig. 25. Dr. Willi Kalender and diagram illustrating the spiral scanning process.

All of the CT methods up until then (1989), including single- and multi-slice scanning, had one thing in common: the thickness and location of each imaged slice within the body was determined during the scanning and data acquisition phase. The relation of the scanning x-ray beam to the long (head to foot) dimension of the human body was fixed, or not moving, as each individual slice was scanned and data was acquired. This produced a data set for each slice. After scanning and acquiring data for a specific slice the body was moved to the next slice position. This was sometimes described as the "scan and step" method where the data for a body section was acquired step by step with a data set for each individual slice. The evolutionary and valuable feature of the spiral method was the acquisition of data in one continuous *volume data set* as illustrated in Fig. 26.

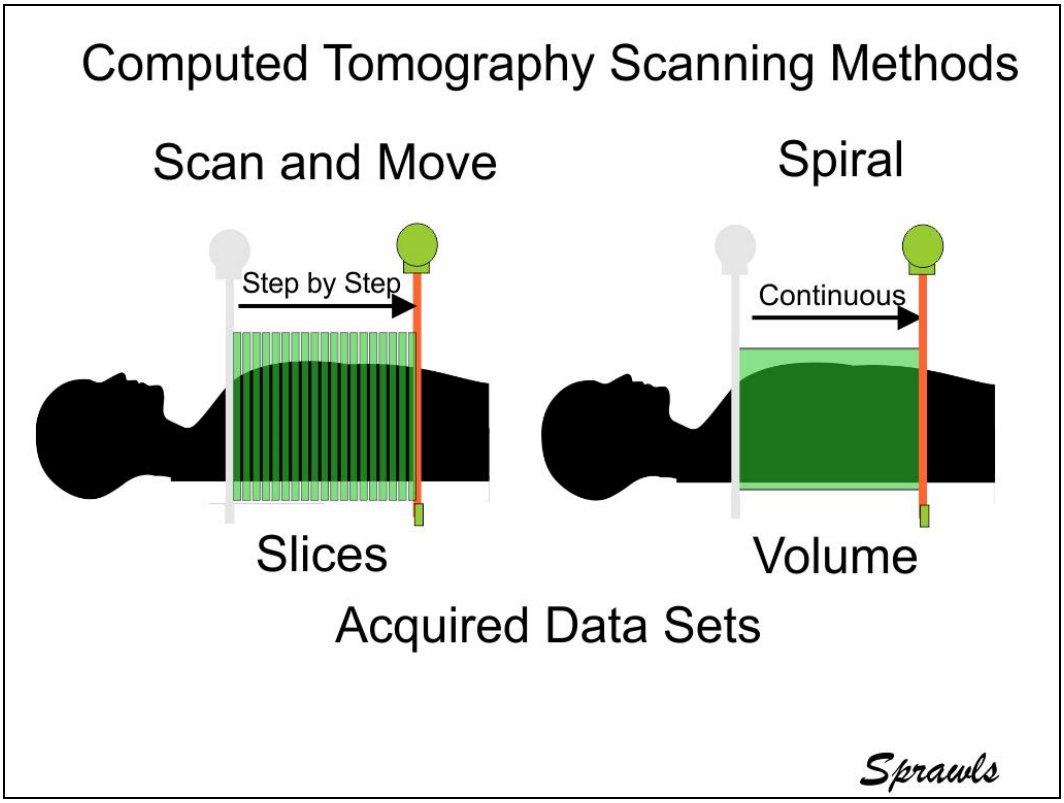

Fig. 26. Comparing scanning methods and acquired data sets.

There were many advantages of spiral scanning and continuous volume data sets over the slice data sets with the other scanning methods (Ref. 14). It overcame the problem of mis-registration of the acquired data with respect to anatomical location. The volume data sets could be used for the reconstruction of three-dimensional (3D) and multiplane images that were especially valuable for angiography and evaluation of vascular diseases. It also revolutionized tomographic (slice) imaging. Rather than the tissue slices being defined (thickness and location) during the acquisition process, they are formed during the reconstruction process from the volume data with the ability to adjust factors including thickness, location, and orientation of the slices. A possibility with the volume data set acquired with spiral scanning was being isotropic with the same detail (spatial resolution) in all directions. This is compared to conventional slice scanning where the slice thickness (one dimension of the voxel) is fixed during the acquisition and is usually larger than the voxel dimensions in the plane of the image.

The Pitch

With the ability to produce data with high detail in the axial direction there were limiting factors. These include the detector and focal spot size effects as in slice acquisition and the additional factor of "how fast" the body is moved through the x-ray beam in the axial direction.

The critical factor that impacts both image quality and radiation dose is the distance the x-ray beam is moved along the length of the body during one rotation in relation to the width of the x-ray beam. This is defined as the *pitch.* It is an adjustable protocol factor with spiral scanning and data acquisition that plays a major role in the optimization of CT imaging procedures and is illustrated in Fig. 27.

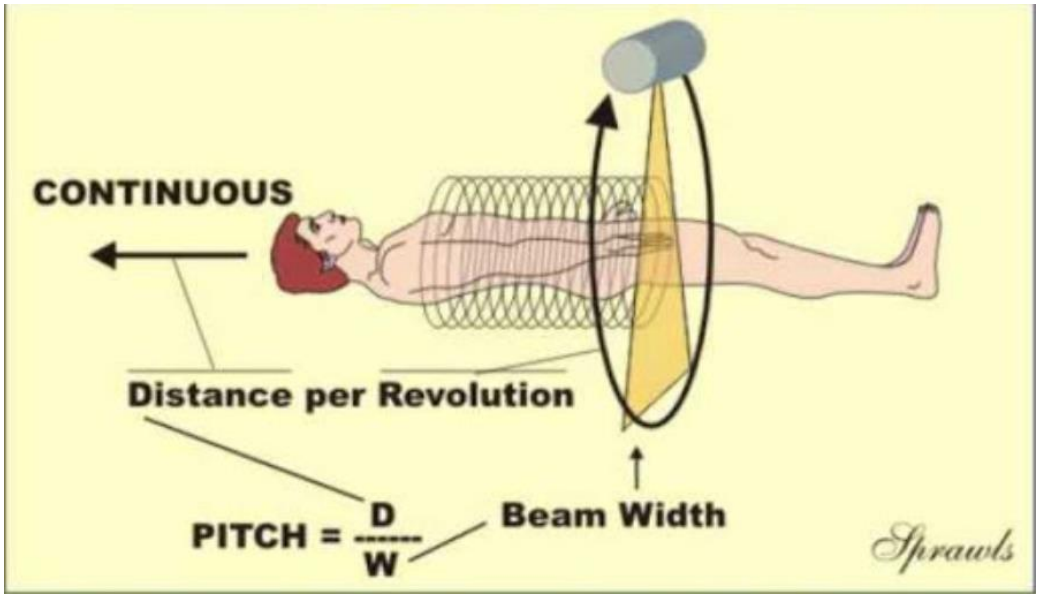

Fig. 27. The concept of the pitch factor shown here for scanning with a single slice beam.

The pitch is a protocol factor that controls and is adjusted before each acquisition scan. The selected value has a significant effect on the three major factors--scan speed, image quality, and radiation dose to the patient. It is a critical factor in optimizing an imaging procedure, especially the balance of image quality and dose.

A significant characteristic of spiral scanning is the determination of the thickness of the tissue slice in the image which has a significant effect on image quality. With the previous generations and methods the slice thickness was determined at the time of acquisition by the active thickness of the x-ray beam as determined by the focal spot and detector sizes. With spiral scanning the slice thickness is not determined, but is *limited* by the x-ray beam thickness. If thin slices (for image detail) are to be produced during reconstruction the data must be acquired with thin x-ray beams. The blurring produced by beam thickness limits the ability to reconstruct thin slices with good quality.

The continuous movement of the patient body during spiral scanning has the effect of blurring the data in the axial direction and this carries over to the reconstructed image. The selected pitch value controls this blurring. Increasing the pitch provides the advantages of faster scanning and reduced radiation dose to the patient. This must be balanced against the reduction of image quality in the slice thickness direction.

Technical Requirements for Spiral Scanning

Spiral scanning required the development of a system more advanced and different from previous types to provide for continuous and many rotations around the patient body. This was achieved with the use of slip ring technology as illustrated in Fig. 28.

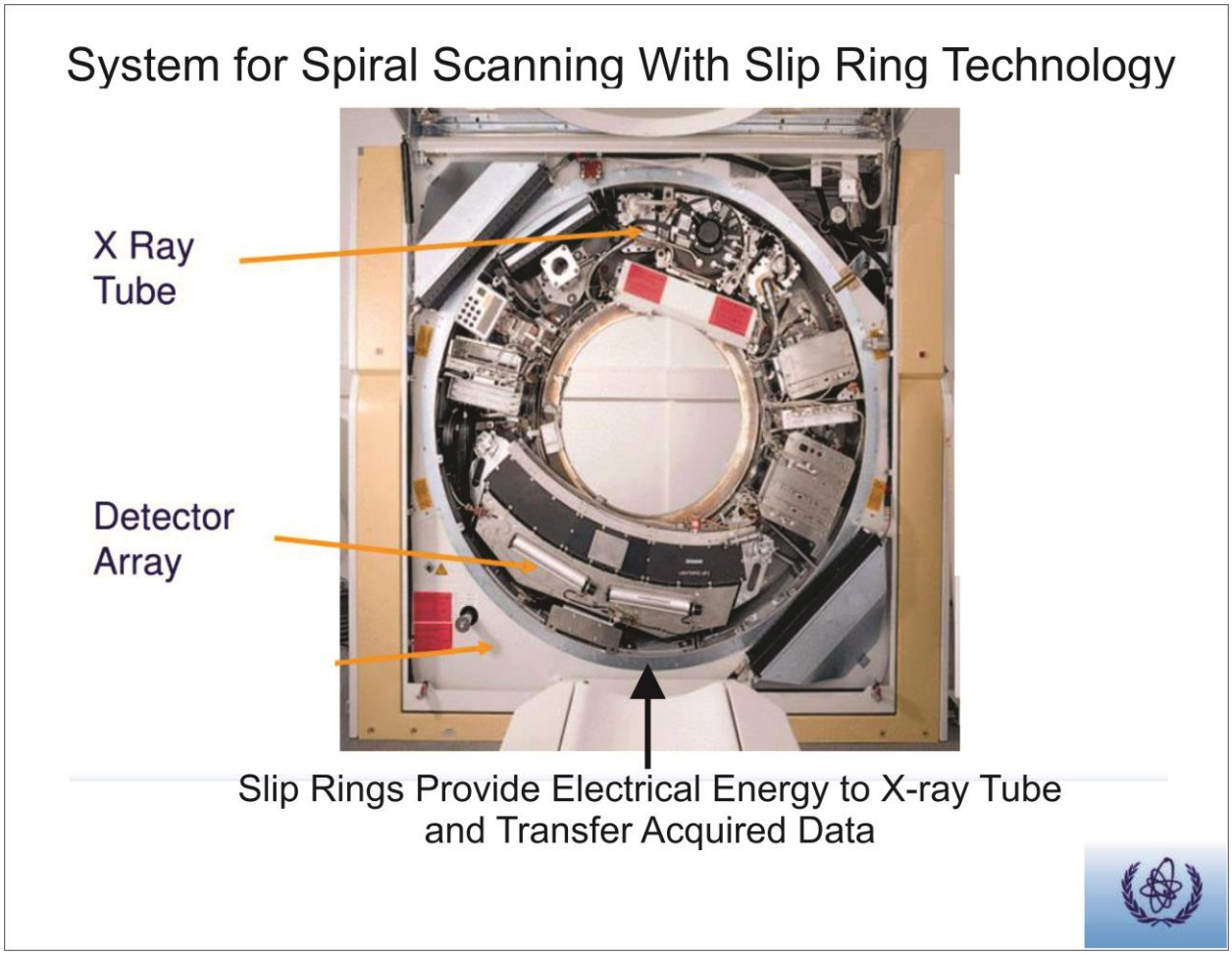

Fig. 28. A scanner using slip ring technology to provide for continuous rotations around the patient's body.

The slip rings are a set of stationary circular electrical/electronic contacts surrounding the rotating components that include the power supply and x-ray tube in addition to the detectors and acquisition data electronics. These connect to the slip rings through sliding contacts during the rotation.

Reconstruction Requirements for Spiral Imaging

One of the major features and values of spiral CT is the ability to produce images for slices created during the reconstruction process from a volume data set. This is different from the other CT methods in which a data set is fixed or confined to each slice during the acquisition phase. A requirement for reconstructing images from data acquired with spiral scanning is *interpolation* from the spiral pathway of the x-ray beam and data acquisition to a slice within the body with a specific location, thickness, and orientation.

XIII. SUMMARY AND THE SIMULTANEOUS DEVELOPMENTS

Our objective with this article is to follow the innovations and developments of the technology for CT systems that provided imaging capabilities for a wide range of clinical applications and are the general purpose systems in most hospitals and clinics, from the early inventions and developments up through the revolutionary spiral scanning process. This has been a

step-by-step process moving through multiple generations with a focus on reducing acquisition time (from minutes to sub-seconds) with increased image quality and more dose-efficient and optimized procedures. This progress has benefited from developments in other fields including detector technology and digital computing capabilities.

Along with the developments of the general purpose CT systems which have been our subject there are many other innovations that contribute to a wider range of clinical applications and improved radiation dose management.

Image Reconstruction

Mathematical image reconstruction that is the foundation of CT has evolved with many innovations including an extensive range of filters/algorithms for optimizing reconstruction. Iterative reconstruction was a major innovation that made it possible to produce images of adequate quality with reduced radiation to patients.

Radiation Dose Management

An ongoing effort, especially by physicists, has been the development of methods and procedures for determining and specifying radiation dose to patients and incorporating that into clinical practice as features of modern CT systems. This has been especially significant because a CT procedure compared to radiography requires higher exposures to produce quality images.

Cone Beam Acquisition

The development of flat panel detectors as used in digital radiography provided the opportunity for an even larger acquisition area beyond the well-established multi-row detector configurations. One advantage was an acquisition covering the full anatomical region from each x-ray beam position as illustrated in Fig. 29.

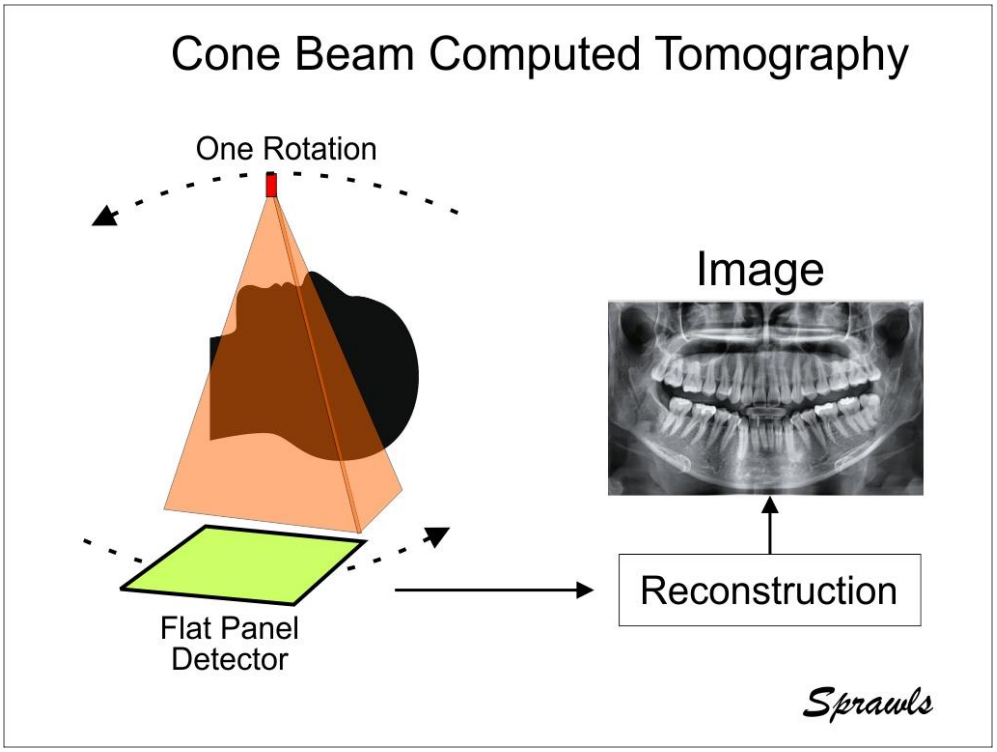

Fig. 29. The concept of cone beam computed tomography.

The cone beam technology was not to become a "next step" in advancing general purpose CT for most clinical applications throughout the human body but enabled the development of specialized CT systems for applications not provided for by general purpose scanners. Two of these systems were for dentistry and breast imaging.

Dual Energy Acquisition

The revolutionary characteristic and contribution of CT to medical imaging was its high contrast sensitivity and ability to produce visible image contrast from small physical differences (physical contrast) among soft tissues. This physical contrast is primarily differences in physical density with some contributions from differences in atomic number (Z). One approach to enhancing contrast is to scan and acquire data with two different x-ray spectra. Contrast is derived from the difference in x-ray attenuation at the different x-ray energies. Several different methods have been used to produce scanners with dual-energy capability. These include two separate x-ray tubes, switching the KV applied during a scan, and spectral selective detectors.

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BIOGRAPHIES

The history of technological developments in computed tomography includes the biographies of those who made major contributions. The innovations and developments over the first fifty years are from the efforts of many physicists, engineers, and physicians often working in collaborative teams in both academic and commercial laboratories. Their contributions are documented and preserved in the scientific literature. Here we provide short biographies of four who made major contributions that have been described in this publication.

Allan MacLeod Cormack

Allan Cormack was born in South Africa in 1924, and after completing the Bachelor and Masters degrees at Cape Town went to St. John's College, Cambridge, as a Research Student.

"I worked at the Cavendish Laboratory under Prof. Otto Frisch on problems connected with He^6. While I made some progress on these problems I did not complete them because of the following circumstances. I had met an American girl, Barbara Seavey, in Dirac's lectures on quantum mechanics, and a year and a half later I wanted to marry her, but I was broke. An inquiry at the Physics Department at Cape Town elicited not only the information that there was a vacancy there, but also a telegram offering me a position as Lecturer. So in 1950 I returned to Cape Town with a bride but no cyclotron, and so no further work on He^6."

In his new position he also served as a part-time medical physicist in the radiology department in Cape Town. This was his introduction to the use of radiation for both diagnosis and treatment of cancer patients. He became concerned with the deficiencies with images and applications for radiation therapy planning and began research and a series of experiments to find some solutions.

Sir Godfrey Newbold Hounsfield

He was born in 1919 and reared near a village in Nottinghamshire and enjoyed the freedom of the rather isolated country life. At a very early age he became intrigued by all the mechanical and electrical gadgets which even then could be found on a farm: the threshing machines, the binders, the generators. The period between his eleventh and eighteenth years was special because this was the time of his first attempts at experimentation, which might never have been made had he lived in a city. "In a village there are few distractions and no pressures to join in at a ball game or go to the cinema, and there was freedom to follow the trail of any interesting idea that came my way." He constructed electrical recording machines; made hazardous investigations of the principles of flight, launching himself from the tops of haystacks with a home-made glider. He almost blew himself up during exciting experiments using water-filled tar barrels and acetylene to see how high they could be waterjet propelled.

During this time he was learning by the hard way many fundamentals in reasoning. At the Magnus Grammar School in Newark they tried hard to provide a broad education but he responded only to physics and mathematics with any ease and moderate enthusiasm.

Aeroplanes were a special interest and at the outbreak of the Second World War he joined the RAF as a volunteer reservist. He took the opportunity to study the books which the RAF made available for Radio Mechanics. After sitting a trade test he was immediately taken on as a Radar Mechanic Instructor and moved to the then RAF-occupied Royal College of Science in South Kensington and later to Cranwell Radar School. At Cranwell, in his spare time he sat and passed the City and Guilds examination in Radio Communications. While there he also occupied himself in building a large-screen oscilloscope and demonstration equipment as aids to instruction, for which he was awarded the Certificate of Merit.

At that time his work was appreciated by Air Vice-Marshal Cassidy who was responsible for his obtaining a grant to attend Faraday House Electrical Engineering College in London, where he received a diploma.

From Hounsfield's Autobiography
"I joined the staff of EMI in Middlesex in 1951, where I worked for a while on radar and guided weapons and later ran a small design laboratory. During this time I became particularly interested in computers, which were then in their infancy."

Robert S. Ledley

Robert Ledley was born in Flushing, Queens in 1926. He studied physics at Columbia hoping that would be his career. However, his parents, worried about the scarcity of jobs in the field, urged him to become a dentist. After receiving his D.D.S. from New York University in 1948, he enrolled as a graduate student at Columbia to study physics. He received his master's degree in physics in 1950.

After his discharge from the Army, he went to work in Washington at the National Bureau of Standards' Dental Materials Section, where he also helped his wife get a job, as a programmer on the Standards Eastern Automatic Computer, or SEAC. It was she who introduced him to computers. Before long he was working directly with the SEAC and focusing on the role that computers might play in solving biomedical problems.

In 1956, Dr. Ledley was hired as an assistant professor of electrical engineering at the George Washington University School of Engineering and Applied Science. That year, he began to collaborate with Lee B. Lusted, a radiologist and electrical engineer, on developing ways to teach physicians and biomedical researchers to use electronic digital computers in their

work. In 1960 he founded the National Biomedical Research Foundation, a nonprofit organization dedicated to promoting the use of computing methods among biomedical scientists.

Willi Kalender

Please See: https://en.wikipedia.org/wiki/Willi_A._Kalender#Career

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MEDICAL PHYSICS DEVELOPMENT IN SOUTH-EAST ASIAN FEDERATION OF ORGANIZATIONS FOR MEDICAL PHYSICS (SEAFOMP): 2000 - 2020

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I. INTRODUCTION AND TWENTY YEARS OF SEAFOMP

The South-East Asian Federation of Organizations for Medical Physics (SEAFOMP) started in the year 2000. This year, we celebrate the 20th anniversary of the federation. This article intends to review the development, progress and achievement of the medical physics profession of the Southeast Asian region, to commemorate this important milestone.

SEAFOMP was formed in an informal discussion in 1996 during the International Organization of Medical Physics (IOMP) World Congress at Nice, France. The founding members were Anchali Krisanachinda, Kwan-Hoong Ng, Agnette de Perio Peralta, Ratana Pirabul, Djarwani S. Soejoko, and Toh-Jui Wong. It was only in 2000, four years later, that the federation was officially accepted as a regional chapter of the International Organization of Medical Physics (IOMP) at the Chicago World Congress [1, 2]. SEAFOMP started with five (out of 10) member countries of the Association of Southeast Asian Nations (ASEAN), namely Indonesia, Malaysia, Philippines, Singapore, and Thailand. Brunei and Vietnam joined in 2002 and 2005, respectively [1-3].

The objectives of SEAFOMP are to promote:

- Co-operation and communication between medical physics organizations in South East Asian region.
- Medical physics and related activities in the region.
- The advancement in status and standard of practice of the medical physics profession.
- To organise and/or sponsor international and regional conferences, meetings or courses.
- To collaborate or affiliate with other scientific organizations.

One of the most important events that the federation organised is the South East Asian Congress of Medical Physics (SEACOMP). The event was initially started as a biennial event. However, it has proven to be an important activity that is crucial in promoting every aspect of the federation objectives that it has since been organized almost every year, rotating amongst the member countries. Table 2 shows the list of SEACOMPs organised over the last 20 years. In the last few years, SEAFOMP has also been co-organising the SEACOMP and Asia-Oceania Congress of Medical Physics (AOCMP) with the Asia-Oceania Federation of Organizations for Medical Physics (AFOMP) – both neighbouring Regional Organizations of IOMP. In 2016 IOMP held its International Conference on Medical Physics ICMP2016 in Bangkok, together with SEACOMP and AOCMP, while in 2021 Singapore will host the IUPESM World Congress on Medical Physics and Biomedical Engineering. This synergistic combination is extremely useful towards enhancing interactions, facilitating knowledge and cultural exchange in the medical physics

community within the larger region of Asia and beyond. The number of delegates has grown from just over 100 to more than 600. In 2020, the 18th SEACOMP & 20th AOCMP is expected to be held in Phuket, Thailand on October 8-10, 2020 with the theme "Medical Physics-Achievements, Challenges and Horizons".

II. POPULATION AND GDP OF SEAFOMP COUNTRIES

Southeast Asia (SEA) countries have a broad diversity in terms of their land size, population, and gross domestic product (GDP). **Table 1** shows the demography of the SEAFOMP countries including some MPs in each country. Brunei Darussalam (subsequent as Brunei) has the smallest land area and population among all the SEAFOMP countries, however, it has the highest number of MPs per million population (18.2). This is followed by Malaysia (10.7), Singapore (8.6), Thailand (2.9), Indonesia (1.7), Philippines (1.7), Vietnam (1.6), Myanmar (0.6), Cambodia (0.3) and Laos (0.3). Compared to the statistics reported in 2017 [3], the total number of MPs in the region has increased from 1,027 to 1,423 (28% growth in 3 years). This is a positive trend indicating that the MP profession has received more recognition in this region corresponding to the increased demand. Among all, Indonesia has the highest increment in the number of MPs (+148), followed by Malaysia (+83), Philippines (+80), Thailand (+51), Vietnam (+20), Singapore (+13), Laos (+2). There was no incremental increase of MPs in Brunei and Cambodia from 2017 to 2020, whereas in Myanmar the number of MPs was reduced from 34 to 33.

Table 1. GDP per capita, number of MPs, population and MPs per million population in the Southeast Asia Countries

Country	Land Area (km^2)	GDP Nominal per Capita (USD), 2019 Estimates [4]	Number of MPs, 2017 [3]	Number of MPs, 2020	Population (million), 2020	MPs per million population, 2020
Brunei	5,765	27,871	8	3	0.44	6,8
Cambodia	181,035	1,620	4	4	15.28	0.3
Indonesia	1,904,569	4,163	290	438	261.1	1.7
Lao PDR	236,800	2,670	0	2	7.1	0.3
Malaysia	329,847	11,136	266	349	32.7	10.7
Myanmar	676,578	1,244	34	33	53.5	0.6
Philippines	300,000	3,294	110	190	109.18	1.7
Singapore	719,2	63,987	35	48	5.6	8.6
Thailand	513,120	7,791	150	450	69.4	6.5
Vietnam	331,210	2,739	130	150	95.5	1.6
Total	**4,486,116**		**1027**	**1667**	**649.8**	**2.6**

III. Radiation Medicine Equipment in SEAFOMP

Radiation medicine equipment has become indispensable in modern medicine. Their presence in a health care facility will often determine the category or classification level of a hospital. Table 2a shows the radiotherapy equipment in SEAFOMP Countries. The total number of external radiotherapy and brachytherapy machines are 396 and 130 machines respectively to give service for around 649,8 million people in ASEAN countries, In South-East Asia (SEA), Thailand, Indonesia, and Malaysia have the most number of external beam radiotherapy equipment.

On the other hand, for the number of brachytherapy equipment, the top three countries are Thailand, the Philippines, and Indonesia as described in Table 2.b. For CT scanners, the biggest numbers are found in Indonesia, Thailand and the Philippines. However, for the number of general radiography, fluoroscopy/interventional radiology, mammography, and dental x-ray machines, the top three countries are Thailand, Indonesia and Malaysia.

In nuclear medicine, only Malaysia and Cambodia still have conventional gamma cameras. Vietnam, Thailand, and Singapore have the largest number of SPECT units as indicated in Table 2.c. For hybrid imaging modalities, Thailand and Malaysia have the biggest number of SPECT/CT units, with the Philippines, Singapore and Vietnam coming in third; while Malaysia, Singapore,

and Thailand have the biggest number of PET/CT scanners. Vietnam, Thailand and the Philippines are the top three countries having cyclotrons.

Brunei, Malaysia, Singapore and Thailand each has more than one EBRT per 1 million population. However, each South East Asian country has at least one ROMP per EBRT. It must be emphasized that the number of medical physicists in a country must be appropriate to the number of sophisticated radiation medicine equipment it acquires. Unfortunately, this is not the case in diagnostic radiology and nuclear medicine in South East Asia. It is imperative that education and training of medical physicists be ramped up to keep up with the demand.

Table 2.a. Radiotherapy Equipment in SEAFOMP countries

Country	EBRT*	Brachytherapy	Simulator: X/CT/MR
Brunei	2	1	1
Cambodia	2	1	NA
Indonesia	74	20	46
Lao PDR	1	NA	1
Malaysia	67	19	2
Myanmar	20	7	10
Philippines	66	31	48
Singapore	20	4	12
Thailand	94	31	66
Vietnam	50	16	36
Total	**396**	**130**	**222**
Machine/Mio	**0,61**	**0,20**	

* EBRT: External beam radiotherapy

Tabel 2.b. Diagnostic Radiology Equipment in SEAFOMP Countries

Country	CT	Fluoro/IR	Mammo	Dental	General Radiography	Magnetic Resonance Imaging
Brunei	8	7	3	14	13	3
Cambodia	25	14	10	15	122	12
Indonesia	4933	1221	956	230	1456	400
Lao PDR	76	3	10	2	7	3
Malaysia	3427	711	279	257	3629	104
Myanmar	1603	53	137	31	125	NA
Philippines	2593	309	354	137	217	118
Singapore	245	83	100	150	380	NA
Thailand	9725	2085	903	456	8226	208
Vietnam	NDA	NDA	NDA	NDA	NDA	NDA
Total	22635	4486	2752	1292	14175	
Equip./Mio	34,83	6,90	4,24	1,99	21,81	

- NDA - no data available

Tabel 2.c. Nuclear Medicine equipment in SEAFOMP countries

Country	SPECT	SPECT /CT	PET/CT	Gamma Camera	Cyclotron
Brunei	NA	1	1	NA	1
Cambodia	NA	NA	NA	1	NA
Indonesia	7	8	3	NA	3
Lao PDR	0	0	0	0	NA
Malaysia	11	13	21	12	3
Myanmar	2	7	2	0	1
Philippines	10	10	12	0	4
Singapore	12	10	16	9	3
Thailand	22	29	15	0	5
Vietnam	24	10	12	NA	6
Total	88	88	82	22	26

IV MEDICAL PHYSICISTS IN SEAFOMP

Among the population of 649.8 million, the number of medical physicists in SEAFOMP is 1667 (Table 1). The average ratio of one medical physicist covering one million of the population is 2.6 per million. Four countries that are above the average ratio are Brunei, Malaysia, Singapore and Thailand. The employment in SEA of medical physicists started 1950 in radiotherapy and nuclear medicine. The percentage distribution of the total number of medical physicists now is as follows: in radiotherapy - 50%, in nuclear medicine - 10%, in diagnostic radiology - 30%, and in other fields - 10%.

Developments in technology in diagnostic radiology and nuclear medicine has also led to the employment of many medical physicists especially in radiation protection, radiation safety, radiation dosimetry, quality management and quality standards. Employment in hospitals of diagnostic radiology medical physicists started in the 1990's in Malaysia, Indonesia, the Philippines, and Thailand. The establishment of education and clinical training programmes led to an increase in medical physicists. However, because the number of diagnostic radiology centres is rapidly increasing in each country in comparison to nuclear medicine centres, there are more diagnostic radiology than nuclear medicine medical physicists. The development of hybrid systems such as SPECT/CT, PET/CT and PET/MR also require cooperation among DRMPs and NMMPs. More interaction among ROMPs, DRMPs and NMMPs, more clinical training programmes, and more education programs are needed.

Table 3. Number of Medical Physicists in Sub-Disciplines

Country	Radiation Oncology	Diagnostic Radiology	Nuclear Medicine	Other Sub-Discipline	Total
Brunei	2	NA	1	NA	3
Cambodia	4	0	0	NA	4
Indonesia	114	306	18	NA	438
Lao PDR	2	NA	NA	NA	2
Malaysia	126	53	28	135	342
Myanmar	24	2	7	NA	33
Philippines	106	36	15	33	190
Singapore	39	9	10	3	61
Thailand	295	100	55	NA	450
Vietnam	123	1	30	NA	154
Total	833	507	163	171	1682
Ratio	0.50	0.30	0.10	0.10	1.00

Table 4. Professional Society Establishments

Country	Year Established	First President	Membership	
			Per cent of Male	Per cent of Female
Brunei	Not yet	NA	NA	NA
Cambodia	Not yet	NA	NA	NA
Indonesia*	2015	Dr. Supriyanto Ardjo Pawiro	65	35
Lao PDR	Not yet	NA	NA	NA
Malaysia	1990	Prof Dr Ng Kwan Hoong	60	40
Myanmar	2016	Mr.Aung Thaung	24	76
Philippines	1986	Ms. Agnette de Perio Peralta	44	56
Singapore	1998	Mr Wong Toh Jui	56	44
Thailand	2001	Prof. Dr.Anchali Krisanachinda	41	59
Vietnam	2008	Dr Phan Sy An	77	23

* New name of professional society which is come from merging two organizations between HFMBI (1990) and IKAFMI (1988)

V. EDUCATIONAL DEVELOPMENT

The establishment of an academic programme in medical physics greatly contributes to its development in any country. The first MSc Medical Physics programme in the region was established in 1971 in Mahidol University, Bangkok. Thailand now has five universities offering an MSc Medical Physics degree, one of which, Chulalongkorn University, also offers a PhD Medical Physics degree. The second oldest MSc Medical Physics programme in the region was established in 1981 in the University of Santo Tomas (UST), Manila. UST established a second degree in 2004, the non-thesis Master in Medical Physics programme. To date, it is still the only university in the Philippines offering the programme although three universities have plans to establish their programmes in the future.

The third oldest MSc Medical Physics programme in the region was established in 1995 in Universiti Sains Malaysia. Currently, Malaysia has two universities, the University of Science Malaysia and the University of Malaya, offering both a master's and a doctoral degree in medical physics. The USM offers a BSc Applied Science (Medical Physics) degree. The Master of Medical Physics programme offered by the University of Malaya is accredited by the Institute of Physics and Engineering in Medicine (IPEM), UK.

Indonesia started a master of medical physics course at Universitas Indonesia in 2002 Currently, Indonesia has six universities offering an MSc Medical Physics degree, four of which also offer a PhD Medical Physics degree. Also, five universities initiated a minor programme in BSc degree; so in total 11 universities offer an elective programme of Medical Physics in their Bachelor Programme. Two universities in Singapore, Nanyang Technological University and National University Singapore, offer a BS Physics degree with a minor or concentration in Medical Physics. One of these two offers Medical Physics as a research degree in its PhD programme. This is similar to the situation in Brunei with Universiti Brunei Darussalam offering a BSc Applied Physics with a Medical Physics module and a PhD in Applied Physics, major in Medical Physics. On the other hand, Vietnam has thirteen (13) BSc Physics and Engineering degree programmes with limited medical physics-related subjects. In 2018, a BSc Medical Physics programme was established in Nguyen Tat Thanh University, this programme was evaluated and confirmed by an IAEA expert to have satisfied the requirement of an MS Medical Physics programme as stated in IAEA-TCS 56; the difference was purely semantic. The remaining South East Asian countries of Cambodia, Laos, and Myanmar currently do not have academic programmes in medical physics. However, IAEA fellowships have enabled young medical physicists from Cambodia, Laos, Myanmar and Vietnam to study for their master's degree in Thailand and Malaysia and to undergo clinical training after their academic studies.

Table 5. Established Academic Post-graduate Degree Programmes in MP (MS / Ph.D.)

Country	Name of University	Curriculum	Academic Programme	Year Established	Graduates per year
Brunei	NA	NA	NA	NA	NA
Cambodia	NA	NA	NA	NA	NA
Indonesia	Universitas Indonesia	Physics (Medical Physics)	BSc, MS, PhD	2002 and 2017	15 and 2
	Institut Teknologi Bandung	Physics (Medical Physics)	MS, PhD	2003	10 and 3
	Universitas Brawijaya	Physics (Medical Physics)	MS, PhD	2009, and 2016	7 and 1
	Universitas Diponegoro	Physics (Medical Physics)	MS	2011	10
	Universitas Hasanuddin	Physics (Medical Physics)	MS	2015	10
	Institut Teknologi Sepuluh Nopember	Physics (Medical Physics)	MS, PhD	2016	6 and 2
Malaysia	University of Malaya	Medical Physics	MMedPhys, PhD	1999	12
	University of Science Malaysia	Medical Physics	BSc Appl Sc. (Medical Physics), MSc, PhD	1995	20
Myanmar	NA	NA	NA	NA	NA
Philippines	University of Santo Tomas Graduate School	Medical Physics	MS Applied Physics	1981	3 (average)
	University of Santo Tomas Graduate School	Medical Physics	Master in Medical Physics	2005	1 (average)
Singapore	Nanyang Technological University	PhD	Applied Physics	2011	1
Thailand	1. Mahidol University:	Medical Physics	MS	1971	6
		Medical Physics	MS	1980	4
	2. Chiangmai University	Medical Physics	MS	2001	6
	3. Chulalongkorn University	Medical Physics	MS, PhD	200, 2015	6
	4. Naresuan University	Medical Physics	MS	2014	4
	5. HRH Princess Chulabhon College of Medical Science, Chulabhon Royal Academy	Medical Physics	MS	2019	9
Vietnam	Nguyen Tat Thanh University	Medical Physics	BSc*	2017	NA

*: Essentially an MS programme, national regulation only allows BSc at the moment

VI TRAINING COURSES AND WORKSHOPS

Structured clinical training of medical physicists was established in SEAFOMP in 2007 under the IAEA Regional Cooperative Agreement. The structured programme on clinical training in medical physics started with Radiation Oncology, followed by Diagnostic Radiology and then Nuclear Medicine Medical Physics in centres with facilities, supervisors and residents. The programme is two years in duration with trainees required to produce a small research project and make a presentation during a medical physics professional society meeting. The competency assessment involves written, practical and oral examinations with external assessors. Passing these examinations serve as proof that the individual can now work independently as a medical physicist. In 2016 IAEA introduced AMPLE – an advanced medical physics learning environment which is an on-line programme to support the remote supervisor. Usually, senior medical physicists are available in hospitals with facilities for clinical training. Residents who are working at a cancer centre but lack a supervisor can share a clinical supervisor from the university hospital under the AMPLE programme.

Even a resident from neighbouring countries such as Laos, Myanmar and Cambodia can share Thai supervisors for ROMP, DRMP and NMMP. SEAFOMP has been quite successful in the clinical training of medical physicists using the IAEA-developed clinical training modules as the programme has had 5 to 6 batches in Thailand, the Philippines, Malaysia, and Indonesia, and a couple of batches in Singapore. Medical physicists from ASEAN countries which have no medical physics education or clinical training programmes can also apply to IAEA to obtain a scholarship to study and/or to undergo clinical training in medical physics. Thailand and Malaysia have received some of these medical physicists. Meanwhile, in Vietnam, aspiring medical physics students undergo at least 9 to 12 months of clinical training in a specific government hospital and then work for at least 1 to 2 years under a medical physics supervisor.

Table 6. Clinical Training of Medical Physicists

Country	Centres	Curriculum	Year established	No. of Graduates	Resident
Brunei	NA	NA	NA	NA	NA
Cambodia	Cambodia	ROMP	2020		1
Indonesia	Cipto Mangunkusumo Hospital	ROMP	2017	5	7
	Dharmais Cancer Center	ROMP			
	MRCCC Siloam Hospital	ROMP			
	Pasar Minggu Hospital	ROMP			
	UI University Hospital	DRMP	2017	0	1
	Dharmais Cancer Center	DRMP			
	Dharmais Cancer Center	NMMP	2020	0	2
	Hasan Sadikin Hospital	NMMP			
	MRCCC Siloam Hospital	NMMP			
	Universitas Indonesia + all training centres	Assoc MP	2018	141	33
Malaysia	Kuala Lumpur Hospital	ROMP	2010-2012	3	3
	Sime Darby Medical Center	ROMP	2010-2012	3	3
	Serdang Hospital	DRMP	2012-2017	1	1
	Sultanah Rahimah Hospital, Klang	DRMP	2012-2017	0	1
	University Malaya Medical Center	DRMP	2012-2017	1	6
	Institut Kanser Negara	ROMP	2018- 2020	on going	2
	Kuala Lumpur Hospital	ROMP	2018- 2020	on going	5
	Penang Hospital	DRMP	2018- 2020	on going	1
	Sulatanah Bahiyah Hospital	DRMP	2018- 2020	on going	1
	Sulatanah Aminah Hospital	DRMP	2018- 2020	on going	1

	University Malaya Medical Center	DRMP	2018- 2020	on going	2
	Institut Kanser Negara	NMMP	2018- 2020	on going	1
	Kuala Lumpur Hospital	NMMP	2018- 2020	on going	1
	University Malaya Medical Center	NMMP	2018- 2020	on going	2
Philippines	Makati Medical Center	ROMP	2009-2011	1	
	Saint Luke's Medical Center	ROMP	2009-2011	1	
	Univ of Perpetual Help Medical Center	ROMP	2009-2011	1	
	Makati Medical Center	ROMP	2012-2015	1	
	Saint Luke's Medical Center	ROMP	2012-2015	1	
	Univ of Perpetual Help Medical Center	ROMP	2012-2015	1	
	Makati Medical Center	ROMP	ongoing		
	Saint Luke's Medical Center	ROMP	ongoing		
	Univ of Perpetual Help Medical Center	ROMP	ongoing		
	Philippine General Hospital	ROMP	ongoing		
	University of Santo Tomas Hospital	ROMP	ongoing		
	JR Reyes Memorial Medical Center	ROMP	Ongoing		
	Lung Center of the Philippines	ROMP	ongoing		
	Chong Hua Medical Center	ROMP	ongoing		
	Southern Philippines Medical Center	ROMP	ongoing		
	Davao Regional Medical Center	ROMP	ongoing		
	Philippine Oncology Center	ROMP	ongoing		
	Asian Hospital and Medical Center	ROMP	ongoing		
	JR Reyes Memorial Medical Center	DRMP	2010 - 2013	1	
	East Avenue Medical Center	DRMP	2010 - 2013	1	
	Philippine Heart Center	DRMP	2010 - 2013	2	
	National Kidney & Transplant Institute	DRMP	2010 - 2013	2	
	University of Santo Tomas Hospital	DRMP	2010 - 2013	1	
	East Avenue Medical Center	DRMP	ongoing		
	Philippine Heart Center	DRMP	ongoing		
	Quirino Memorial Medical Center	DRMP	Ongoing		
	National Kidney & Transplant Institute	DRMP	Ongoing		
	University of Santo Tomas Hospital	DRMP	Ongoing		
	Philippine General Hospital	DRMP	Ongoing		
	Cardinal Santos Medical Center	NMMP	Ongoing		
	Makati Medical Center	NMMP	Ongoing		
	Saint Luke's Medical Center	NMMP	Ongoing		
	National Kidney & Transplant Institute	NMMP	Ongoing		
	Philippine Heart Center	NMMP	Ongoing		
Singapore	Singapore General Hospital	NMMP	2016-2020	2	

	National Cancer Centre Singapore	ROMP	2014-2020	6	
Thailand	King Chulalongkorn Memorial Hospital	ROMP	2006-2008	10	
	Siriraj Hospital	ROMP			
	Ramathibodi Hospital	ROMP			
	Chiang Mai Hospital	ROMP			
	King Chulalongkorn Memorial Hospital	DRMP	2008-2010	5	
	Bumrungrad International Hospital	DRMP			
	King Chulalongkorn Memorial Hospital	NMMP	2011-2013	12	
	Siriraj Hospital	NMMP			
	Ramathibodi Hospital	NMMP			
	Chiang Mai Hospital	NMMP			
	King Chulalongkorn Memorial Hospital	ROMP/DRMP	2016-2018		
	Siriraj Hospital	ROMP/NMMP			
	Ramathibodi Hospital	ROMP/DRMP		15 (ROMP)	
	Chiang Mai Hospital	ROMP/NMMP		4 (DRMP)	
	Prince of Songkla University	ROMP		3 (NMMP)	
	Chulabhon Hospital	ROMP			
	Pinlon Hospital Myanmar	ROMP/NMMP			
	King Chulalongkorn Memorial Hospital	ROMP	2018-2020		
	Siriraj Hospital	ROMP/DRMP			
	Ramathibodi Hospital	ROMP			
	Chiang Mai Hospital	ROMP			
	Prince of Songkla University	ROMP/DRMP/NMMP			
	Chulabhon Hospital	ROMP			14(ROMP
	Ratchaburi Cancer Center	ROMP			5(DRMP)
	Udonthani Cancer Center	ROMP			3(NMMP)
	Sawanpracharak Hospital	ROMP			
	Suratthani Cancer Center	ROMP			
	Pinlon Hospital Myanmar	ROMP			
	Mittaphap Hospital, Laos	ROMP			

VII COMMUNICATION, NEWSLETTERS, CONFERENCES

Since 2001, SEAFOMP has held a series of congresses to share the scientific and clinical knowledge and mutual support among its members. This annual congress is called the South East Asian Congress for Medical Physics (SEACOMP). SEACOMPs were held respectively in Malaysia (Kuala Lumpur, 2001, 2004 and 2018), Thailand (Bangkok, 2003 and 2016; Chiang Mai, 2009 and 2012), Indonesia (Jakarta, 2006; Bandung, 2010, Yogyakarta 2015, Bali 2019), the Philippines (Manila, 2007; Manila & Bohol, 2011, Iloilo 2017), Vietnam (Ho Chi Minh City, 2008 and 2014) and Singapore (2013).

The communication among the members in SEAFOMP is an important key for the organization. Through email, not only the information but also knowledge is shared among the members. The vote regarding many issues on SEAFOMP is done with this mode of communication. During the SEACOMP, the executive committee meeting is also held.

In the future, the SEAFOMP plans to publish a newsletter for the members. This newsletter intends to communicate messages and information to members. The clinical experience from the experts can also be shared in this newsletter.

Table 7. History of SEACOMP [1]

Date	SEACOMP	Venue	Congress Theme	No. Of delegates
23 - 24 April 2001	1st SEACOMP	Kuala Lumpur, Malaysia	Continuous Quality Improvement In Medical Imaging And Radiation Therapy	110
12-14 November 2003	2nd SEACOMP	Bangkok	Enhancing Quality In Imaging And Therapy In South-East Asia	150
27 - 29 September 2004	3rd SEACOMP & 4th AOCMP.	Kuala Lumpur	Progress And Innovations In Medical Physics	220
7 - 11 November 2006	4th SEACOMP	Jakarta	Physics Contribution To Human And Biosystem	126
21 -23 November 2007	5th SEACOMP	Manila, Philippines	Saving Lives Through Physics And Engineering	124
29 – 31 Oct 2008	6th SEACOMP and 8th AOCMP	Ho Chi Minh City, Vietnam	Nurturing Collaborations In Medical Physics	305
22 – 24 October 2009	7th SEACOMP And 9th AOCMP	Chiang Mai, Thailand	Update In Medical Physics	303
10 -13 December 2010	8th SEACOMP	Bandung, Indonesia	Improvement In Medical Science And Technology For Better Life	131
16 – 19 November 2011	9th SEACOMP	Manila and Bohol	Celebrating Gains And Meeting New Challenges In Medical Physics	115
11 – 14 December 2012	10th SEACOMP	Chiang Mai	The Convergence Of Imaging And Therapy	202
12–14 December 2013	11th SEACOMP & 13th AOCMP	Singapore	Advancing Imaging And Radiotherapy With Medical Physics	271
23-25 October 2014	12th SEACOMP & 14th AOCMP	Ho Chi Minh City, Vietnam	Medical Physics For Advanced Medicine	239
10-12 December 2015	13th SEACOMP	Yogyakarta, Indonesia	Improving The Quality Of Human Health Through Physics	196
9-12 December 2016	14th SEACOMP 16th AOCMP 22nd ICMP	Bangkok, Thailand	Medical Physics Propelling Global Health	645
December 1 - 3, 2017	15th SEACOMP	Iloilo, Philippines	Medical Physics Towards Health For ALL	177
11 – 14 November 2018	16th SEACOMP & 18th AOCMP	Kuala Lumpur, Malaysia	A Sustainable Future For Medical Physics	529
8 to 10 August 2019	17th SEACOMP & 3rd PIT-FMB	Bali, Indonesia	Improvement On Patient Care And Safety Through The Innovation In Medical Physics	320

VIII. IAEA REGIONAL PROJECTS

The regional Project of Medical Physics in Asia Pacific Region RAS6038 as indicated in Table 8 started in 2003 with the title "Strengthening medical physics through education and training." The goal of the first project is to develop clinical training programmes for medical physicists in the disciplines of radiation oncology medical physics (ROMP), diagnostic radiology medical physics (DRMP) and nuclear medicine medical physics (NMMP). The goal of extension of the project (2007 – 2011) is to facilitate the clinical training trial in the region based on IAEA training course series numbers 37, 47 and 50 for ROMP, DRMP, and NMMP. In SEAFOMP members, Malaysia, the Philippines, Thailand and Singapore participated in the clinical training trials [3].

The next phase of the regional project of Medical Physics RAS6077 (2014 – 2017) was proposed to initiate the Advanced Medical Physics Learning (AMPLE) platform. This platform transformed the clinical training guide to an electronic system and also included the e-learning material in the Moodle platform. This project also initiated trials in Indonesia, Malaysia, the Philippines, and Thailand to test the platform. There is some remote supervision from Thailand for clinical training in Myanmar and Vietnam [1]. This project is continued with regional project RAS6087 (2018 – 2021) which facilitate the clinical training trial with AMPLE platform.

Besides regional projects under the Regional Coordinated Agreement (RCA), the non-agreement project which was proposed by Malaysia, Indonesia and Pakistan is also funded for 2018-2021 to provide support for the project "Strengthening Education and Clinical Training Programmes for Medical Physicists in the Asia Pacific region and East Asia region". This project has a budget to provide support for capacity building training for medical physicists in the region. With this project, 12 workshops in the fields of radiotherapy, diagnostic radiology and nuclear medicine physics have been planned.

Table 8. Regional Projects on Medical Physics in the Asia Pacific Region

Project Number	Title	Duration	Lead Country Coordinator
RAS6038	RCA Project – strengthening medical physics through education and training	2003 – 2007	Mr. John Drew (Australia)
RAS6038 (extension)	RCA Project - strengthening medical physics through education and training	2007 – 2011	Mr. John Drew (Australia)
RAS6077	RCA Project - Strengthening the effectiveness and extent of medical physics education and training	2014 – 2017	Dr. Ian Donald McLean (Australia)
RAS6087	RCA Project - Enhancing Medical Physics Services in Developing Standards, Education and Training through Regional Cooperation	2018 – 2021	Dr. Ian Donald McLean (Australia)
RAS6088	Non-Agreement Project - Strengthening Education and Clinical Training Programmes for Medical Physicists	2018 -2021	Dr. Noriah Jamal (Malaysia)

IX. CONCLUSION AND THE FUTURE

The spirit of ASEAN resounds in SEAFOMP. The idea of setting up an organization for South-east Asian medical physics societies was first mooted in 1996. The South-East Asian Federation of Organizations for Medical Physics (SEAFOMP) was officially accepted as a regional chapter (now IOMP Regional Organization) of the IOMP at the Chicago World Congress in 2000 with five member countries, viz. Indonesia, Malaysia, the Philippines, Singapore and Thailand. Today SEAFOMP has ten members.

Looking forward to the future, all members of the SEAFOMP will continue to strive for continual promotion of the medical physics profession by working with international bodies such as IAEA, WHO, and IOMP. We would need to continuously enhance our education and professional development. To sustain this growth, we need to develop a new generation of younger leaders, who are passionate and progressive.

X. Acknowledgement

We would like to express our deep appreciation to Ms. Sophea Ly, President of ACRT, Cambodia and Dr. Dang Thanh Luong, Head of Biomedical Physics Department, Faculty of Medicine, Nguyen Tat Thanh University, Vietnam for the essential contribution.

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HISTORY OF MEDICAL PHYSICS EDUCATION AND TRAINING IN CENTRAL AND EASTERN EUROPE – FIRST CONFERENCES, PROJECTS AND MSC COURSES

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Content

This history paper traces the first conference, projects and courses, associated with the development of medical physics education and training in Central and Eastern Europe (mainly the countries which before the end of the "Cold War" were with limited opportunity for communication with the rest of the world). The fall of the Berlin Wall, and the start of the democratic changes in Central and Eastern Europe since 1989, are undoubtedly some of the historic milestones of the 20th century. In this period of time colleagues from East and West Europe renewed collaboration, which had been dormant for many years.

One of the fields of cooperation was related to harmonisation of education and training in all professions, leading to the future expansion of the European Union. Part of this overall trend were the activities related to development of specific education and training in medical physics in Central and Eastern Europe. The author has initiated and has been actively involved in most of the initial steps of this development.

This brief history addresses specifically the development and introduction of new educational/training programs.

1. The Education and Training Network and the Conference on Medical Physics Education and Training, Budapest 1994

Medical Physics education was one of the main topics to be discussed at the Report of a Joint IAEA-WHO Expert Committee in 1968 [1]. The person representing Central/Eastern European countries at this Committee was O.

Chomicki from Poland (IOMP President 2000-2003). His involvement in this activity, as well as the big number of specialists in the Radium Institute in Poland (founded by Maria Sklodowska Curie as early as in 1932) were the main reason for development of specialised University courses on medical physics in Poland during the 1970s. These are among the first such courses in the world [2]. Before 1989 the rest of the countries in Central/Eastern Europe did not have specific courses in medical physics, but had well established activities and courses in medical engineering and nuclear engineering, which included significant element of the traditional medical physics curriculum.

The necessity for a pan-European forum in the field of Medical Physics & Engineering education and training was discussed on various occasions. The author presented his views on the subject at the 5th Conference of the Bulgarian Society for Biomedical Physics and Engineering held in Sofia, Bulgaria (1988), the 5th Mediterranean Conference on Medical and Biological Engineering held in Patras Greece (1989) [3] and the Weimar Clinical Engineering Workshop in the former GDR (1990). During the Intra-European Workshop held in Szentendre, Hungary in May 1991 (organised by N Richter) [4], it was agreed that there is considerable interest in and need for future collaboration between Central/Eastern and Western European countries in the area of professional education and training, and activities for joint ventures were initiated.

The next steps included formation of Network of active specialists in the field of education and training. Traditionally Medical Engineering education was well developed in Central/Eastern Europe [5] and the Network included many medical engineers. The Network was created by S Tabakov in 1993 and a Bulletin (Fig.3) was made to disseminate information between its members (see the Logo of the Network on Fig.3 – on the banner to the right of the Polish Conference Logo).

In parallel to the Network other inter-university activities took place, notably through the EC projects TEMPUS (a Trans-European Cooperation Scheme for Higher Education). The first such projects were organised by the University of Patras, Greece with Universities from Bulgaria and Romania [6]. These activities triggered the creation of new MSc courses (mainly medical engineering with elements of medical physics).

In 1992 two new MSc programmes were initiated in Bulgaria – an MSc on Medical Physics at the Shumen University and an MSc on Medical Engineering at the Technical University Sofia – branch Plovdiv, while in 1995 a similar University programme was founded in Iasi, Romania.

Following the Network creation a submission was made to the European Commission (EC) for supporting of a Conference on the subject. The proposal was successful [7] what triggered the organisation of the First European Conference on Education in Medical Radiation Physics.

The venue of the Conference was agreed to be in Budapest – a central meeting point for colleagues from Central/Eastern and Western Europe. The objectives of the Conference were:

- To increase the East/West European co-operation in the field of Medical Physics;

- To establish the status and needs of education and training in Medical Radiation Physics in Central/Eastern European countries;

- To formulate proposals for the advancement of post-graduate education in Medical Radiation Physics and identify resource sharing initiatives;

- To consider the need for a Training Authority and a professional network in the field of Medical Physics & Engineering in Central/Eastern Europe.

The Organising Committee was set up in London with members: C Roberts, S Tabakov, C Lewis, assisted by V Tabakova and D Smith. The Local Organising Committee was set up in Budapest with members: P Zarand, N Richter, I Polgar. Emails were rare at that time, hence most of the organisation was handled through facsimile exchanges.

The European Federation of the Organisations for Medical Physics (EFOMP) was also involved in the Conference, the concept of which was accepted enthusiastically in almost all countries invited to participate. The delegates to the conference were senior medical physicists, each being a nominee of their European professional society and/or

their University. In total 37 Institutions, Societies and Universities from 23 European countries were represented at the Conference. This Conference was very important for EFOMP, as it allowed the leadership of the Federation to meet their senior colleagues from Central/Eastern Europe.

The European Conference on Post-graduate Education in Medical Radiation Physics was held in Budapest from 12-14 November 1994. It included presentations about the current status of medical physics education and training in each of the present countries and organisations. Two general discussions (round tables) followed which focused on two major themes:
- education and accreditation of centres for education & training;
- training and continuing professional development.

The Delegates to the Budapest Conference (Fig.1) represented EFOMP and the Societies of most European countries. Papers about the status quo were collected from: Austria, Belarus, Belgium, Bulgaria, Croatia, Cyprus, Czech Rep, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Netherlands, Poland, Portugal, Romania, Russia, Slovakia, Spain, Sweden, Switzerland, Turkey, Ukraine, UK (13 Central/Eastern European countries were presented). Additionally information was presented from EFOMP, IFMBE (International Federation of Medical and Biological Engineering) and IAEA (International Atomic Energy Agency).

All presentations from the Conference were later included in the book "Medical Radiation Physics – A European Perspective", editors C Roberts, S Tabakov, C Lewis, King's College London, 1995 (Fig.2). The book [8] was also published as an electronic PDF book (on a floppy disk) and distributed in most Medical Physics Societies in Europe and the world (more than 1000 copies of the book and the diskette were distributed). The diskette with the electronic book was one of the first e-books in the world.

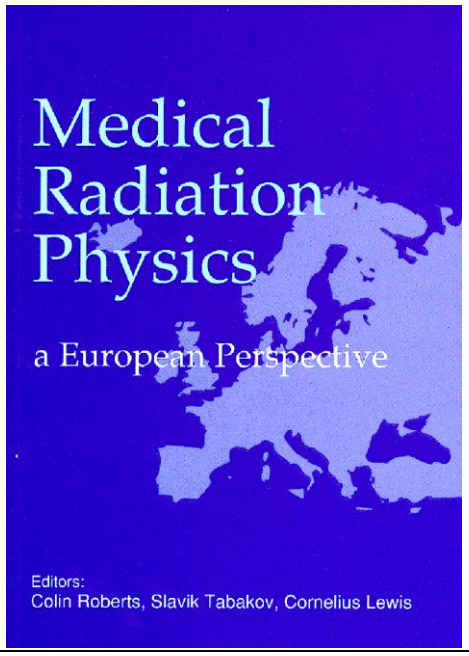


Fig.1 Some of the delegates to the European Conference on Post-graduate Education in Medical Radiation Physics was held 12-14 November 1994, Budapest. The Delegates to the Conference included: C Roberts, S Tabakov, C Lewis, P Zarand, N Richter, I Polgar, M Radwanska, F Milano, M Ribas-Morales, J Gomes da Silva, V Orel, V Laginova, S Kovacova, L Musilek, W Selentag, S Aid, M Gershkevich, S Sheriff, M Vrtar, Y Lemoigne, P Frangopol, N Sheahan, A Vaitkus, C Milu, H Zackova, I Stamboliev, B Proimos, A Karadjov, I-L Lamm, P Trindev, M Morawska-Kaczinska, I Tarutin, S Spyrou, A Benini, G Pawlicki, Y Dekhtyar, D Gubatova, V Tabakova, D Smith, G Kemikler, I Ozbay, T Ratner, A Noel, B Aubert.

Fig.2 - Book following the Conference (distributed all over Europe).

This book triggered many new MSc-level medical physics courses in Eastern Europe. The author later used the model of this Conference to support the development of medical physics courses in some South-East Asian countries (see further in the paper).

A number of activities between countries were initiated immediately after this Conference, including the projects EMERALD and ERM, as well as the projects with the Baltic countries (these will be described further in the paper). In Budapest was also the first presentation of the European Scientific Institute (ESI) in Archamps, which later became one of the main Schools of the EFOMP [9]. The Conference also stimulated the Societies from Eastern Europe to join EFOMP. As a result the number of national members societies of EFOMP increased significantly after the Budapest Conference.

The Conference delegates made a review of the current situation, revealing main areas of improvement in most of the existing MSc programmes curricula, such as inclusion of specific specialist topics. A weakness associated with the practical training was lack of structure and uniform method for training delivery. Specific strengths were noted as the traditionally good education in maths and physics in Central/Eastern Europe, the good computer literacy and radiation protection activities [10]. The Conference emphasized that the best way forward is creating new MSc programmes, specific for medical physics, and also the need of professional translation of medical physics terminology (this was realised later through the projects EMIT and EMITEL, developed and coordinated by the author [47]). The need of specific curricula for development of new MSc courses and Training schemes was emphasized. This was addressed through the projects ERM and EMERALD (described further in the paper).

It was agreed that collaboration between the East/West European countries is essential for the advancement of the profession and a Declaration of Intent was signed by all delegates (see Fig. 10). The Network was further expanded and its first meeting was agreed to be associated with the Conference of Medical Physics in Krakow, Poland (September 1995), organised by M Radwanska (Fig.3). The Network had its own Bulletin (edited by the author at King's College London). The Network members were instrumental in starting new educational activities.

Fig. 3 The first workshop of the European Network on Medical Physics Education and Training at the 10th Congress of the Polish Society of Medical Physics (1995, Krakow, Poland, part of the delegates).
The logo of the Network Bulletin is added to the lower left corner.

2. Project ERM – the Inter-University Centre for Education in Medical Physics and its Curriculum

Immediately after the Budapest 1994 Conference the author initiated an EU project in Bulgaria (the project ERM - acronym for Education for Radiation in Medicine) [11] in parallel with the project EMERALD. This was a natural continuation of the Conference objectives for strengthening East/West European relations. The project was submitted to the newly established EU programme TEMPUS (a Trans-European Cooperation Scheme for Higher Education), one of its objectives was to support the synchronisation of Eastern European University education with this at the European Union (EU).

The selection of Bulgaria for this project was underpinned by the fact the before 1990 the author had worked in the Medical University Plovdiv Bulgaria and had the necessary local support there. Additionally during 1988-89 the author developed and presented at the MEDICON Conference in Patras, Greece (September 1989) an effective educational model for small countries starting their new education in medical engineering and medical physics, using International Education/Training Centres [3]. These ideas and expertise were applied in the project ERM.

The project included partners from the Budapest Conference: King's College London, UK (led by C Roberts and S Tabakov), University of Florence, Italy (led by F Milano), Trinity College Dublin, Ireland (led by N Sheahan). The Bulgarian counter-parts were: Medical University Plovdiv (led by A Djurdjev and I Delov, later K Velkova), the Technical University (TU) – branch Plovdiv (led by L Genov and G Stoilov) and later the University of Plovdiv (PU) Chair Atomic Physics (led by N Balabanov). Contractor was C Roberts and Coordinator S Tabakov.

The project ERM objective was to introduce MSc/Diploma degree course in Medical Radiation Physics plus short CPD courses in the field of radiation applied to medicine. The project was supported by SIEMENS, IAEA, EFOMP, The Bulgarian Academy of Sciences, The Bulgarian Ministry of Health and The Parliament of Bulgaria - this being one of the first projects to introduce the widely used in Europe two-tier university degree system of Batchelor - Master into the education in Bulgaria (the system previously used in Bulgaria was 'Diploma-degree', equivalent to Master, and based on 5 years University education). The project was also supported by the Bulgarian Scientific Societies of Biomedical Physics and Engineering and of Roentgenology, Radiology and Radiobiology, as well as the UK Institute of Physical Sciences in Medicine (IPSM, currently IPEM) [12].

The project ERM was initiated during October 1995. Its first year included founding and equipping a new Educational Centre (space was provided by Medical University - MU Plovdiv) and at the same time organising all lecturers in the international team to exchange information and begin the preparations of the syllabi of the modules and related books with lecture notes. The project plan was to develop for every module of the MSc programme its own textbook with lectures in English. This was important as such books were not yet available in Eastern Europe or were too expensive. These books (in total 20 textbooks with lecture notes) were used in many other countries (see further). The curricula and modules syllabi (see Annex 1) developed in ERM project were later shared with colleagues planning to develop similar MSc programmes in other countries.

The course was developed as one academic year fully modularised course, consisting of 12 modules, divided in three parts – here below is the structure of the MSc curriculum:

- Part 1 - Basis of Medical Physics (including modules in the field of Human Anatomy, Radiation Physics, Radiation Detection and Measurements, Radiobiology);

- Part 2 - Special subjects of Medical Physics (including education on the principles and equipment of Radiotherapy, Diagnostic Radiology, Nuclear Medicine, and other Imaging modalities);

- Part 3 - Continuing Professional Development CPD (this part includes subjects on Radiation Protection, Hospital Safety, Medical Informatics and European Integration, which were developed for the MSc students, but were additionally open to external medical specialists applying radiation (as CPD courses).

TERM 1 (MSc Curriculum Part 1: September - December)

1. Basis of Human Anatomy and Physiology (approx. 90 acad. hours; test assessment)
2. Radiation Physics (approx. 90 acad. hours; exam)
3. Radiation Detection and Measurements (approx. 90 acad. hours ; exam)
4. Radiobiology (approx. 60 acad. hours, test assessment)
5. Physics and Equip. of Ultrasound, Lasers, MRI (approx. 90 acad. hours, exam)

TERM 2 - 1st part (MSc Curriculum Part 2: January - March)
6. Physics and Equipment of Diagnostic Radiology (approx. 80 acad. hours, exam)
7. Physics and Equipment of Nuclear Medicine (approx. 80 acad. hours, exam)
8. Physics and Equipment of Radiotherapy (approx. 80 acad. hours, exam)
9. Image and Signal Processing in Medicine (approx. 60 acad. hours, test assessment)

TERM 2 – 2nd part (MSc Curriculum Part 3: April - May)
10. Radiation Protection and Hospital Safety (approx. 80 acad. hours, tests, Certif.)
11. Medical Informatics (approx. 30 acad. hours, test)
12. European Integration (approx. 30 acad. hours, test)
Awarding Post-graduate Diploma in Medical Physics

MSc Research Thesis development (approximately 5 months, April to September)

All education was planned to be conducted in English and this was one of the entry requirements for the students. A specific feature of the Curriculum was that it included both physics and engineering aspects of the specialist modules, thus allowing students to work, if necessary, also as service engineers – a useful activity for a small country. Each module was based on condensed delivery (1 to 3 weeks) to allow external lecturers to visit the Centre. Each module had its Bulgarian module Organiser and European module Adviser. Each Bulgarian lecturer visited his/her counterpart to adapt their model of lecturing and several Workshops were made to synchronise all modules. The names of all lecturers to the Inter-University Centre are listed in ANNEX 1.

The Bulgarian Universities in the project signed declarations allowing mutual recognition of the MSc in Medical Physics degrees, and the MSc Diplomas were signed by the Rectors of all participating Bulgarian Universities. This way all three Universities (each having specific speciality – medicine, engineering, physics) made their first Inter-University Centre. The Universities were sharing their Laboratories for the needs of the Centre (MU allowed use of its medical equipment in the late afternoons). All lecturers received honorary status to the Centre – either as visiting lecturers or visiting professors to MU and PU. All these activities were approved by the Academic Councils of the three Bulgarian Universities and during the spring of 1997 the Centre was officially established.

The official opening of the ERM Inter-University Centre and the start of its first academic year was at the beginning of September 1997. It included all lecturers, students and project supporters. The ceremony attracted dignitaries from the Government, the Parliament, the City Council and many Institutions and Societies, including the Rectors of the three Bulgarian Universities (Fig. 4).

Fig. 4 Opening of the Inter-University Centre for Medical Radiation Physics ERM, 1997, Plovdiv Bulgaria

The achievements of the Centre and its MSc programme were reported at the World Congress in Nice (WC2007). The lecture notes, structure of curriculum, modules syllabi (see ANNEX 1) and experience of this Centre were later used in the forthcoming Tempus projects with the Baltic States and in a number of other countries.

At that stage the author repeated an experiment made during 1990 (also in Plovdiv) – a test to evaluate the difference between alphanumerical memory and image memory of the students. We used tasks explained verbally and explained mainly through images, and were asking the students to perform the tasks and evaluate how they had understood these. In both cases the students were showing 80% better understanding when using images - something all lecturers had experienced from practice. The results from these tests underpinned the need to use Educational Image Databases in the teaching process (this being one of the main tasks in the EMERALD project).

The first applications of our EMERALD e-learning materials were in this Centre and in the ICTP College on Medical Physics 1996-1997 [13].

In order to be able to publish the ERM Lecture Notes (Fig. 5) a legal body associated with the Centre was established – the Foundation "Physics Engineering Medicine XXI" FIM XXI (Физика, Инженерство, Медицина XXI, ФИМ XXI). The Foundation was led by S Tabakov and N Balabanov.

During 1999 the ERM MSc course received UK accreditation through the UK IPEM – this being the first non-UK based MSc course in Medical Physics with such accreditation. The MSc course continued its delivery in English at the Inter-University Centre in the Medical University until 2003. Later it was delivered and examined in Bulgarian (however using the English text books, hence knowledge of the language was an entry requirement). Later the MSc course was transferred to the University of Plovdiv and continues successfully until now.

The graduates from this MSc course work in various hospitals in Bulgaria and abroad. The ERM MSc programmes provided a model, which was useful for other countries, as discussed later. The original syllabi of its modules are presented in ANNEX 1 to this paper.

3. The Project for development of medical physics education in the Baltic countries

Soon after the start of the ERM project the author worked with colleagues from Riga Technical University and University of Linköping (Y Dekhtyar and A Oberg) to develop a similar educational project for the three Baltic states - Latvia, Estonia and Lithuania.

Fig. 5 The set with MSc lecture notes of ERM project, Published in Plovdiv, Bulgaria

Fig. 6 Book with Baltic Curricula and Syllabi, Published in Riga, Latvia

The Objective of the project was: development of a new Joint Baltic Medical Engineering and Physics Master course (JBMEP) on the basis of developing new educational modules and restructuring of some existing modules on Medical/Biomedical Engineering and Physics (including their teaching materials) delivered as part of various MSc programmes in the universities of Latvia, Lithuania and Estonia [14].

The project partners were: Linköping University, Sweden (represented by A Oberg, Contractor and P Ask); Riga Technical University, Latvia (represented by Y Dekhtyar, Co-ordinator and I Knets); Kaunas Technical University, Lithuania (represented by A Lukosevicius and D Adliene); Tallinn Technical University, Estonia (represented by H Hinrikus and K Meigas); University of Tartu, Estonia (represented by A. Soosaar and P-H. Kingisep); University of Latvia (represented by J Spigulis and M Auzinsh); King's College London (represented by C Roberts, J Lee and S Tabakov).

This project started in mid-1998 and developed quite quickly by using the significant experience from the ERM project, and many teaching materials (from ERM and EMERALD projects). Additionally, the Universities in Kaunas and Tallinn already had medical engineering courses.

In 1999 Estonia hosted the Nordic Baltic Conference on Biomedical Engineering in Tallinn, where a joint Workshop [15, 16] was made on the Education in medical physics and medical engineering (Fig.7). This International Conference was supported both by the IFMBE and the International Organization for Medical Physics (IOMP was represented by O Chomicki and S Tabakov). The Conference was attended not only by colleagues from the European Nordic countries, but from representatives of more than 30 countries (Conference organisers were H Hinricus and K Mejgas). The development of the profession in the Baltic countries continued with steady progress and in 2008 Latvia hosted the Nordic Baltic Conference on Biomedical Engineering in Riga, where a similar Workshop took place (Organiser Y Dekhtyar).

The structure of the joint Baltic MSc course was different from the ERM MSc course – in the Baltic project the students had to travel (for some of the modules) between the countries, but this was facilitated by the fact that the distances were small and there were no border problems.

The Coordinator Y Dekhtyar was also helped by A Katashevs and they set up a Teaching Centre in Riga. The Centre had its own laboratories. These laboratories included old decommissioned medical equipment, which was revived and maintained for training purposes only. This was an excellent asset for the students. These activities in Latvia led to quick development of medical physics in the country.

Fig.7 The International Advisory Committee of the 11th Nordic Baltic Conference on Biomedical Engineering, 1999, Tallinn, Estonia

The Baltic project received all ERM Lecture Notes and EMERALD Training Tasks and Image databases. A number of EMIT project training tasks (another training project, discussed further in the paper) were tested through the students there. Some colleagues from this project took part later in the EMITEL project [47] – they were the main translators of the Dictionary terms in Latvian, Estonian and Lithuanian, as well as taking part in writing some entries for the Encyclopaedia of Medical Physics.

The Baltic project revealed significant need for specialists in medical physics and engineering in the three countries. While EFOMP minimal requirements at the time were for about 20-30 medical physicists per country of this size, the rapid healthcare development in the Baltic countries predicted figures of c. 200 medical physicists and engineers per country. These figures are yet to be achieved, however ten years later the overall number of medical physicists and engineers in these three countries was around 200. Without doubt this Tempus project contributed significantly to this rapidly increased number of such professionals in the Baltic region. The members of the Baltic project Consortium (Fig.8) continued actively in further educational, professional and research activities in their countries.

The Curriculum development in the Baltic project included development of new modules and restructuring of existing modules in the Baltic Universities. This created a number of specific specialist modules. The number of modules and their syllabi formed a considerable list of options (24 modules in biomedical engineering and 17 modules in medical physics). These were published in the book Baltic Biomedical Engineering and Physics MSc Courses [17] - Fig.6.

The Baltic MSc-level Curriculum was designed to be delivered over 2 years. Each country had the freedom to include various combinations of the optional modules, thus creating a flexible workforce. The structure of this Curriculum was based on credits (one credit being equal to one full week of education).

During the whole project lecturers from the Baltic countries were visiting partners in Sweden and UK, in order to synchronise their educational practices with those in the EU Universities. The project (1998-2001) paved the path for further medical physics and engineering international projects and conferences and proved a boost for the professional development in the Baltic countries.

Later the MSc programmes created in this project continued with the active involvement of Prof F Milano (Florence University), who took part in the lecturing, examination and placements (in Italy) of many Baltic students. Further F Milano transferred his experience from Bulgaria and Latvia in the development of similar medical physics courses in Ukraine (Zhytomyr University).

Fig. 8 The Baltic project Consortium meeting, 2000, Kaunas, Lithuania

4.Assessment of educational courses

The abovementioned MSc programmes developed real examples for establishing of medical physics University courses. Professional evaluation of the quality of these courses was an activity which at that time was performed only by the two largest medical physics societies – the IPEM in UK and the AAPM in the USA.

An attempt to achieve this at international level was made through the EU project TEMPERE (Thematic Network for Training and Education in Medical Physics and Biomedical Engineering). The project (1996-1999) was Coordinated by the University of Patras (Coordinator B Proimos) and included about 40 European Universities and Organisations. The main documents used were policy statements and publications of EFOMP, IPEM, AAPM, HPA, IFMBE, and others, including the Book from Budapest Conference.

The TEMPERE project did not include many Central/Eastern European Universities, but its Conference (satellite to the MEDICON Conference in Patras 1999) had considerable number of participants from this part of the world. The results from the TEMPERE project were published in 2001 (Editor Z Kolitsi) [18]. The recommendations were useful, but it was difficult to be implemented in practice on international level due to the significant variety of national/local regulations.

On a national level the first medical physics MSc programme accreditations were made almost simultaneously by the IPEM (IPSM) in 1994 [19] in the UK and in 1995 in the USA [20]. The accreditation in USA was handled by CAMPEP (Commission on Accreditation of Medical Physics Educational Programs) – this was a collaborative activity of several organisations. CAMPEP was formed in 1994 and initially was supported by AAPM (American Association of Physicists in Medicine), ACR (American College of Radiology (ACR), ACMP (American College of Medical Physics). In 2001 CCPM (Canadian College of Physicists in Medicine) also joined CAMPEP and in 2010 was replaced by COMP (Canadian Organization of Medical Physics).

IOMP made an attempt to initiate accreditation activities in 2005 by forming a Validation and Accreditation Panel (Chaired by S Tabakov and later A Krisanachinda) to its Education and Training Committee (ETC). The first activity of this Panel was to create an IOMP Model Curriculum, which to be used as background for the accreditation [21]. This was developed (using experience from the UK, USA and the ERM project), but was not applied in practice as the accreditation activity required legal obligations, which IOMP could offer only in connection with its legal status (what was achieved in 2017). However the IOMP Model Curriculum was used, together with the ERM and EMERALD materials, as one of the founding blocks of the IAEA Training Course Series No. 56 (IAEA-TCS-56) - Postgraduate Medical Physics Academic Programmes [22]. This TCS 56 is currently the main quality criteria for international medical physics accreditation.

In 2015 the IOMP President (S Tabakov) and the IOMP ETC Chair (J Damilakis) renewed the IOMP accreditation activities in connection with the expected legal status of IOMP (achieved in 2017) [23]. The Accreditation Manual

of IOMP was prepared as a guide to future applicants [24]. The first IOMP international accreditation was made by S Tabakov and J Damilakis (issued to the ICTP MSc programme in Trieste) – Fig.9. In the following IOMP office the ETC (Chair A Chougule) continued successfully these activities.

Fig.9 First IOMP accredited alumni of MSc Advanced Studies in Medical Physics with supporting colleagues from AIFM

The IOMP Regional Organisation for Europe EFOMP arranged its legal status before IOMP and in 2016 it established the European Board for Accreditation in Medical Physics (EBAMP) as an independent organisation that accredits medical physics education and training courses and events [25].

International accreditation for Training Centres exists on paper but has not been realised as a regular activity at the moment. However another activity – Certification for medical physicists was realised on international level. This activity was initiated in 2008 by R Wu and KY Cheung and was discussed at several IOMP meetings. An independent International Medical Physics Certification Board (IMPCB) was formed, which made a number of certifications – initially for National Certification Boards (as in Hong Kong and South Korea), later for individuals (specifically from the ICTP Master programme in Advanced Medical Physics Studies). IMPCB has Memorandum of Understanding with IOMP, which is one of its main sponsoring organisations [26].

Although these activities are not directly related with Central and Eastern Europe, some colleagues from this part of the world benefitted from the international accreditation and certification. An important moment is that these activities triggered various national activities related to assessment the quality of education and training.

5.Medical Physics Training development in Eastern Europe

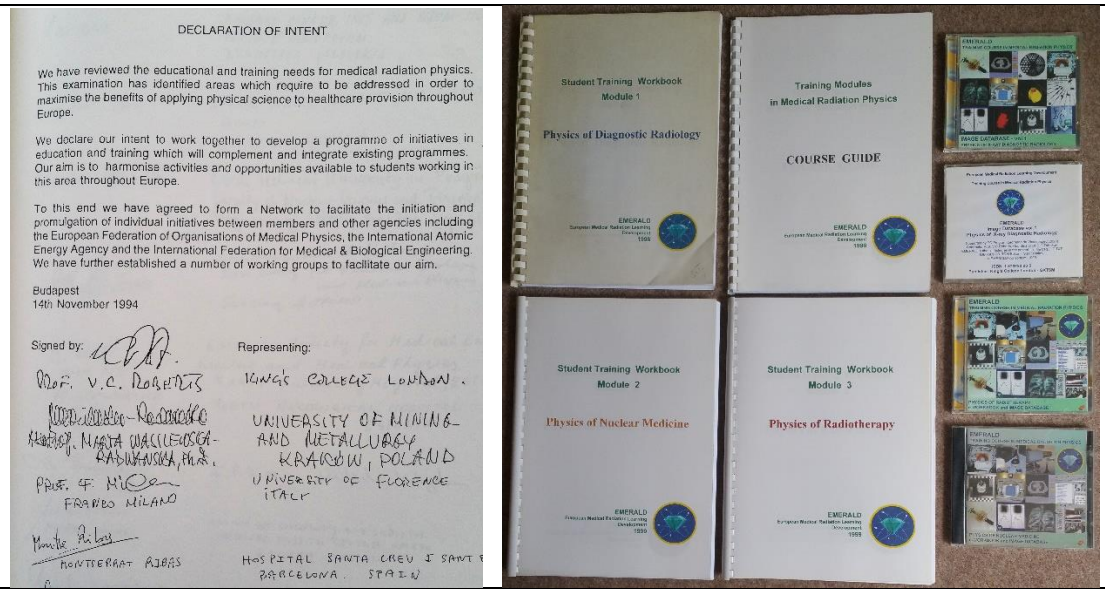
The work on medical physics training in Eastern Europe was going in parallel with the development of MSc courses. This activity was associated with the project EMERALD (1995-1998), developed by the author in collaboration with colleagues from several EU countries [47]. The training of the project EMERALD (acronym of European Medical Radiation Learning Development) was made as a structured training, following industry training examples. The training was associated with purpose-built training tasks, each building specific competencies (as per the IPEM Training scheme competencies at the time). The Curriculum of the training (Training Timetables – see ANNEX 2 to this paper) was made in a way to allow progressive building of competencies, covering the important at the time elements of the main fields of medical physics. The Curriculum was made this way in order to allow easy introduction in countries where previous training in medical physics did not exist. As such it was very useful for the first steps of medical physics training in Central/Easter Europe and other LMI countries. The structure of the Curriculum was made as a compendium of semi-independent tasks, thus allowing easy replacement of old tasks with new training tasks. This provided a continuous frame for the training. EMERALD was later continued with the project EMIT (developed by almost the same team) [47]. EMERALD was addressing training in Diagnostic Radiology (X-ray), Nuclear Medicine and Radiotherapy, while EMIT was addressing training in MRI and Ultrasound Imaging.

EMERALD and EMIT Consortia developed 5 Training modules, each including specific Workbook with Training tasks and Image Database with educational images. Each module was developed with a length of 4 months (80 days). During this time the trainee is expected to acquire most necessary professional skills (as per the IPEM

Training scheme). This part of the training was called “condensed” and can be performed in most countries, where training conditions are set up. Further the trainees can spend several months in their own country/state where they can additionally study the local Regulations and professional requirements.

Each of the modules is based on Training tasks. Each task was given a notional completion time (in days). Achieving completion of 3 modules for 1 year would require very intensive work. However the design of the EMERALD scheme allows the individual modules to be taken separately with intervals between each.

The First International Conference on Medical Physics Training, was organised by S Tabakov under the project EMERALD in ICTP Trieste (24-26 September 1998). It included EFOMP officers and senior delegates from 28 European countries (of these 10 from Central and Eastern Europe, as per the Declaration from Budapest – Fig.10): Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxemburg, Netherland, Norway, Poland, Portugal, Slovenia, Spain, Sweden, Switzerland, UK, Yugoslavia [27]. Additionally there were 8 trainees from 3 countries to give feedback on the usability of the EMERALD e-learning materials. Each delegate to this Conference received the full set of EMERALD Training materials (Fig.11).


DECLARATION OF INTENT

We have reviewed the educational and training needs for medical radiation physics. This examination has identified areas which require to be addressed in order to maximise the benefits of applying physical science to healthcare provision throughout Europe.

We declare our intent to work together to develop a programme of initiatives in education and training which will complement and integrate existing programmes. Our aim is to harmonise activities and opportunities available to students working in this area throughout Europe.

To this end we have agreed to form a Network to facilitate the initiation and promulgation of individual initiatives between members and other agencies including the European Federation of Organisations of Medical Physics, the International Atomic Energy Agency and the International Federation for Medical & Biological Engineering. We have further established a number of working groups to facilitate our aim.

Budapest
14th November 1994

Signed by: Representing:

Prof. V.C. ROBERTS — KING'S COLLEGE LONDON.

UNIVERSITY OF MINING AND METALLURGY KRAKOW, POLAND

UNIVERSITY OF FLORENCE ITALY

HOSPITAL SANTA CREU I SANT PAU BARCELONA. SPAIN

Fig. 10 Declaration of Intent to all Delegates to the Budapest Conference 1994

Fig.11 EMERALD Training materials (given to all delegates of Conference at ICTP, 1998 and Prague, 2000)
The delegates of the First International Conference on Medical Physics Training (Emerald, ICTP, 1998) included: R Nowotny, W Schmidt, P Trindev, V Todorov, M Vrtar, S Spyrou, L Musilek, C-A Jessen, H Hinrikus, K Mejgas, H Escola, A Noel, S Naudy, I Gardin, F Nuesslin, Z Kolitsi, P Zarand, N Sheahan, U Bottigli, V Punys, M Radwanska, U Zdesar, P Smith, S Sheriff, A Rogers, M Tooley, D Saunders, P Andreo, S Andric, S Faermann, C Roberts, S Tabakov, C Lewis, D Smith, V Tabakova, S-E Strand, B-A Johnson, M Ljungberg, F Milano, L Riccardi, A Benini, J Gomes da Silva, N Teixeira, A Pascoal, L Bertocchi.

The discussions at this Conference revealed what type of Training Centres are necessary and how to establish these. The already functioning Training Scheme of IPEM UK was used as a model for organising training activities and the timetable of EMERALD was used as a sample scheme. It was agreed that a specific Seminar is necessary to be made for the colleagues in Central and Eastern Europe.

This additional activity (Euro Seminar on Medical Radiation Physics Training) was organised by S Tabakov and L Musilek in Prague, 3-5 September 2000 (Fig.12, Fig.13). It was attended by senior specialists from EFOMP and from 15 Eastern European Countries: Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Russia, Serbia, Slovakia, Slovenia, Ukraine, Ukraine.

Each delegate was given a full set of all EMERALD e-learning materials – timetables, 4 textbooks with Guide and Training Tasks (in Diagnostic Radiology, Nuclear Medicine and Radiotherapy), 3 CD-ROMs with full image databased in these three fields and Sample Documents for organising the Training Centres and related activities.

The seminar not only introduced the concepts of quality training, but also discussed the development of Medical Physics in this part of the world. It was stated that during the 5 years after the Budapest Conference (1994), almost all Eastern European countries have developed their own Medical Physics University courses (at Master level).

Additional Seminars for the development of Medical Physics Training were made in France, Sweden and Ireland. It was evident that the EMERALD Training materials were used In different degree) in 30 European countries: Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Malta, Norway, Poland, Portugal, Romania, Russian Federation, Serbia, Slovak Rep., Slovenia, Spain, Sweden, UK, Ukraine.

After 2000 all EMERALD materials (and later all EMIT) training materials (training tasks and associated over 3000 images) were included at the first medical physics educational web site, made as part of the project EMERALD II [47]. In 2005 this web site (www.emerald2.eu) was made as open access and continues to serve the profession.

Fig. 12 - Euro Seminar on Medical Physics Training, 2000, Prague, Czechia -part of delegates.
The delegates from Central/Eastern Europe to the Euro Seminar (Prague, 2000) included: E Milieva, P Trindev, M Vrtar, A Santic, H Hinrikus, K Mejgas, P Zarand, N Richter, y Dekhtyar, V Atkocius, D Adliene, N Golnik, G Pawlicki, G Matache, N Loutova, T Ratner, L Zamecnik, Kozlikova, G Kemikler, Lysitsia, Yabloshanska, Z Bozovic, S Andric.

Fig. 13 - Working discussions in the Prague Seminar (with all Emerald materials in blue boxes).

It was natural the next Conference on e-Learning in Medical Physics, organised by S Tabakov in ICTP Trieste, 9-12 October 2003, to include delegates from Central and Eastern Europe (Fig.15). The delegates to this Conference included senior specialists from 26 countries (of those 10 from Eastern Europe and 3 from outside Europe): Austria, Bulgaria, Croatia, Cyprus, Czechia, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Ireland, Cuba, Lithuania, Macedonia, Netherland, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Turkey, Thailand, UK, USA. EFOMP, AAPM, IFMBE and IOMP were also represented at this Conference.

The delegates to this Conference received the EMIT project materials – all as digital publications – 2 CDs with e-books with Training tasks and Image databases related to MRI and Ultrasound Imaging, plus the mini CD with the first edition of the Scientific Dictionary of Medical Physics (Fig. 14). All EMIT materials plus the previous EMERALD materials were also available to the delegates through the web site www.emerald2.eu. The Conference took decisions for the collaborative development of the profession in Europe, what was subject to the special Declaration signed [47]. Project EMIT included EFOMP as a project partner (the first EU project of EFOMP) and was natural the Declaration to be synced with EFOMP officers. The Conference discussed the new EMIT training materials and the use of e-learning in the profession. The successful implementation of e-learning in the profession attracted in 2004 the inaugural EU Award for education – the Leonardo da Vince Award [47].

Approximately at the same period of time the International Atomic Energy Agency (IAEA) increased its series of projects specifically addressing education and training [28, 29]. For an extensive list of projects see [29]. As part of these the author worked on development of new courses and training with specialists from Czech Republic,

Hungary, Belarus, Macedonia, Armenia and Georgia (I Horakova, L Judas, M Yermalitsky, S Tramptova, R Stamenov, K Stepanjan, G Archuadze). Additionally the author took active part in other such educational IAEA projects with Malaysia, Thailand, Jamaica and later Zimbabwe (S Salikin, A Krisanachinda, A Tajuddin, W Kirdpon, M Vouckov, G Azangwe). Further part of the expertise from these activities were transferred to the large IAEA Regional project with Africa. These and other projects led to the sharing our educational curriculum (from Project ERM) and training materials (from projects EMERALD and EMIT) to: Armenia, Belarus, Brazil, Costa Rica, Czech Republic, Estonia, Egypt, France, Georgia, Jamaica, Latvia, Lithuania, Macedonia, Malaysia, Thailand, Zimbabwe. These materials were used in setting and updating MSc programmes and training schemes.

Fig. 14 EMIT Training materials (given to all delegates of Conference at ICTP, 2003) and web site front page

Fig.15 Delegates at the EMIT EuroConference on e-Learning in Medical Physics, ICTP, Trieste, 2003
The delegates to the First Conference on e-Learning in Medical Physics (ICTP, 2003) included: C Lewis, C Deane, A Cvetkov, C Oates, T Jansson, D Goss, G Helms, S Keevil, M Buchgeister, M Stoeva, C vaan Pul, G Clarke, K Nagyova, A Krisanachinda, P Sprawls, Dr Nick Fernando Poutanen, J Young, Y Ider, A Milan, A Rosenfeld, A Simons, R Wirestam, I Hernando, V Gersanovska, P Zarand, P Caplanis, F Stahlberg, C Etard, N Fernando, R Stollberger, P Smith, F Milano, A Lukoshevicius, V Aitken, E Perrin, A Evans, A Briquet, C Bigini, A Paats, M Almqvist, G Boyle, F Fidecaro; in Front: C Roberts, J-Y Giraud, Mr L Torres, S Riches, S Tabakov, I-L Lamm, M Radwanska, S Naudy, R Magjarevic, L Musilek, T Wehrle

In 1998-99, as soon as EMERALD Training and associated e-Learning materials were ready, the author with F Milano and M Radwanska prepared an EC project (alongside EMERALD II) aiming to develop a dedicated Internet server for Medical Physics e-Learning (an “e-Broadcast for education”) to support all countries in Central/Eastern Europe, and later to be expanded for the other LMI countries at the time. The project would be led by our Italian partner F Milano and the main counterpart was in Poland (M Radwanska and a Polish Internet company), where we intended to host the dedicated e-learning server. The project was not accepted for funding as being “well ahead of its time”. This way the idea was not further developed. However the project EMERALD II (EMERALD – Internet Issue) developed in 1999 the first educational web site in the profession (www.emerald2.net, later www.emerald2.eu) which was directed toward training. It was opened free in 2003 to all colleagues from Central/Eastern Europe and the students at ICTP and later was made an open resource to everyone in the profession, as it continues until now, supported by the author.

6. Transferring the experience from Central/Eastern Europe to other Regions

A number of colleagues from the projects described above took part in supporting the development of the profession in other countries. Additionally in this period EFOMP and the IOMP Education and Training Committees supported many activities, with increasing number of these for the countries from Central/Eastern Europe [30, 31, 32], while AAPM organised courses in some of these countries.

One of these activities was organised by the colleagues from the Baltic project – an IAEA supported Seminar and Workshop in 2010 in Kaunas, Lithuania. The book with the materials from this Workshop included information about the current MSc courses in Central and Eastern Europe, which showed the progress of medical physics education in these courses during the 15 years after the Budapest Conference (similar information was included for European, Asian, African and Latin American courses in the book on Education in training from 2011 – to be discussed later). This Seminar and Workshop was led by D Adliene, Y Dekhtyar and M Laurikaitis. The book from Kaunas included also some countries which had not been covered in the other books: Albania, Georgia, Macedonia [33].

The most important disseminator of the activities related to medical physics education and training was the ICTP College on Medical Physics. This international activity was running since 1988. ICTP as institution was a member of the EMERALD Consortium and during 1996 and 1999 tested the EMERALD training programmes. In 2002 the College Co-Directors P Sprawls and S Tabakov changed its curriculum and included special Workshop and sessions focussed on exchange of experience and knowledge related to establishing and running educational programmes. These additional activities were successful and collected significant amount of information about the professional status of medical physics in many countries.

The development of medical physics professional activities, the pioneering of e-learning in the profession and the activities of the ICTP College were part of the presentation of medical physics as part of the applied physics sub-specialities at the UNESCO Conference Physics and Sustainable Development, 2005, Durban, South Africa (co-organised by ICTP). The presentation “Physics and Health” at this High-level Conference was led by P Sprawls and D van der Merwe, with the support of S Tabakov and A Niroomand Rad. The very successful presentation resulted in selecting the field Physics and Health as one of the 4 major fields of applied physics for the 21 century [34]. This activity was essential for the increase of funding for projects related to medical physics in the following years.

Until 2020 the ICTP College on Medical Physics educated over 1000 young colleagues from Low-and-Middle-Income (LMI) countries. These were from: Albania, Algeria, Armenia, Argentina, Bangladesh, Belarus, Bosna, Brazil, Brunei, Bulgaria, Cameroon, P.R. China, Chili, Croatia, Congo, Costa Rica, Columbia, Cuba, Czech Rep., Ecuador, Estonia, Ethiopia, Egypt, Eritrea, Ghana, Guatemala, Honduras, Hungary, India, Indonesia, Iran, Iraq, Jamaica, Jordan, Kenia, Kuwait, Latvia, Lebanon, Lesotho, Lithuania, Libya, North Macedonia, Malaysia, Malawi, Moldova, Mongolia, Mexico, Morocco, Montenegro, Namibia, Nepal, Nigeria, Oman, Peru, Philippines, Papua New Guinee, Panama, Pakistan, Poland, Romania, Russia, Serbia, Senegal, Slovenia, Slovakia, Sudan, Syria, Sri Lanka, South Africa, Tanzania, Trinidad and Tobago, Thailand, Turkey, Uganda, Ukraine, Uruguay, Uzbekistan, Venezuela, Vietnam, Yemen, Zambia, Zimbabwe. More than 1/4 of these from Central and Eastern Europe. Over the years many of the Central/Eastern European countries became members of the European Union and some of them moved out of the LMI category [35].

Each participant to the ICTP College on Medical Physics received a free set of EMERALD and EMIT training materials, Curriculum for MSc programme, full access to the established Sprawls Resources, and full set of lectures notes and Power Point slides. Using these materials and experience many of the colleagues organised spin-off courses in their countries, while some organised MSc courses or re-structured and enriched existing University courses.

The success of the College on Medical Physics led to opening and supporting of other medical physics activities in ICTP – notably various IAEA Courses. In 2015 ICTP started a regular activity - School of Medical Physics for Radiation Therapy (in alternating years with the College). This School is headed by R Padovani, with the support of L Bertocchi. In 2014 ICTP formed an alliance with the University of Trieste, resulting in the first international MSc programme in Medical Physics, headed by R Padovani and R Longo. This MSc on Advanced Studies in

Medical Physics, with IAEA support, has already produced several alumni (including graduates from Central/Eastern Europe) and has the strong support of the Italian Association of Medical Physics (AIFM) [35].

In 2003 the author discussed with N Suchowerska from Australia that the experience from education/training progress in one whole region (Central/Eastern Europe) could be very useful for Asia (and in particular South-East Assia). In this connection a full day Education and Training Workshop was organised by N Suchowerska, K Inamura and S Tabakov, as a satellite event to the World Congress WC2003 in Sydney. The success of this event led to a further similar Workshop (with more countries) as a satellite event to the World Congress WC2006 in Seoul (organised by A Krisanachinda, Kwan Ng and S Tabakov).

The materials from these activities, and from the Workshops of the ICTP College, were gathered and published by ICTP in a new book: Medical Physics and Engineering Education and Training, 2011 [36]. The book included a number of various MSc curricula and was distributed to senior colleagues from almost all LMI countries. It presented an overview of the global progress of medical physics education and training.

Workshop on Education and Training was made also in Moscow, 2010 (Fig.16), satellite to the 3rd Euro-Asian Congress on Medical Physics, supported by the Russian Association of Medical Physics (AMFR). This activity (organised by V Kostiliev, B Allen, F Nuesslin, S Tabakov) identified possibilities for opening of new medical physics educational courses in the regions of Siberia and in the former Soviet republics.

To transfer this experience in Latin America such Workshop on Medical Physics Education/Training was made successfully as satellite to the ICMP2011, Porto Alegre, Brazil (organised by S Tabakov, R Wu, M do Carmo Lopes, P Costa, R Terini, M Freitas). This activity also assessed the possibility for CAMPEP accrediting MSc courses in this part of the world. In 2014 King's College London and the University of Sao Paulo formed a joint project for translation the EMERALD Diagnostic Radiology Training Curriculum and associated Training tasks in Portuguese for use in Brazil [37]. The project included a Workshop Medical Physics Training in Sao Paulo, 2014 with many senior specialists from the country (Fig.17).

Fig.16 Organisers of Workshop on Medical Physics Education and Training, 2010 Moscow

Fig. 17 Participants of the Workshop for dissemination of the Emerald-BR project in São Paulo, 2014, Brazil.

To transfer this experience for developing of MSc courses in Africa, Workshops on Education and Training were held as satellite to the ICMP2013, Brighton, UK (Fig.18), and also as satellite to the WC2015, Toronto (both organised by S Tabakov and F Nuesslin). These Workshops were financially supported by IUPAP and included also specialists from IAEA and WHO. These IOMP-IUPAP Workshops became a traditional collaboration between the two organisations for the support of LMI countries. During ICMP2016 similar Workshop was made satellite to the ICMP2016, Bangkok (organised by S Tabakov, Y Pipman, A Krisanachinda, Kwan Ng, S Pawiro) Fig.19. Another Workshop was held as satellite to the WC2018, Prague (organised by S Tabakov, Y Pipman, L Judas, F Nuesslin), Fig.20.

Fig.18 IOMP-IUPAP-IAEA-WHO Workshop Medical Physics Development in Africa ICMP2013, Brighton, UK

During the ICMP2016 IOMP expanded its activities on the subject to set its own IOMP School, which was repeated at the AOCMP2017, Jaipur (organised by J Damilakis, S Tabakov, M Stoeva, A Krisanachinda and A Chougule). The IOMP School is now a regular activity organised also as a Virtual event with Web-Seminars in 2020 (organised by J Damilakis, M Rehani, A Chougule, M Stoeva).

In the period 2005-2015 the author worked with colleagues from Central/Eastern Europe for the inclusion of their languages in the Multilingual Scientific Dictionary of Medical Physics Terms. This was important as many countries allowed education only in the national language, while most textbooks were on English (and some of the other most popular languages). To further promote the growth of the Dictionary a special Workshop was held with colleagues from Central and Eastern Europe (organised by S Tabakov and V Tabakova, as part of project EMITEL [47]), satellite to the WC2009, Munich, Germany. As a result 13 out of the 32 languages in the Dictionary (40%) are from Central and Eastern Europe: Bulgarian, Czech, Hungarian, Lithuanian, Polish; Estonian, Romanian, Latvian, Russian, Slovenian, Croatian, Georgian, Ukrainian (the teams of translators are listed at the Dictionary and Encyclopaedia web site www.emitel2.eu) [38].

These many activities resulted in significant increase of medical physicists in Central/Eastern Europe. The increased confidence in the professional status of these countries led to selecting Sofia, Bulgaria to host the European Conference in Medical Physics in 2012, and the same year Czech Republic was selected to host the World Congress 2018 in Prague.

Fig.19 IOMP-IUPAP Workshop Education and Training with IAEA participation, Bangkok, ICMP2016

Fig.20 IOMP-IUPAP Workshop on Education and Training with IAEA participation, Prague, WC2018

This brief history addresses specifically activities related to the organisation of new educational courses and associated training. The next step – introducing in the education novel methods and equipment – is an ongoing process, which has always been led by the largest societies and organisations of the profession. We have to specifically mention here the Summer Courses on AAPM, which in the past 10 years were made available free to colleagues from LMI countries through the Virtual Library [39]. Similarly the regular Summer School which EFOMP organised, has a special role in the updating of the course content.

The EU projects which EFOMP led in the past decade were similarly pivotal for updating the knowledge of all colleagues in Europe. Specific projects were presented in the MPI Journal, together with statistics of their implementation. Some of these projects included activities organised in Central/Eastern European countries [40, 41]. The current free Webinars add further dimension to the update of educational courses (of course, plus

disseminating new knowledge to the colleagues). These activities continue and the colleagues are constantly informed of new short courses or certified activities.

Conclusion

It was obvious from the books in 2010-211 [33, 36] that the profession in Central/Eastern Europe has developed with fast pace for just 15 years. While the book from the Budapest Conference [8] showed only several curricula, the further publications presented confidently their progress in education and training. To make another point-check, we commissioned from EFOMP a paper on the development of education and training in 2018 [42]. This paper was presented at the Workshop at WC2018, Prague (Fig. 20). The author H Hrsak from Croatia had used specific Questionnaire and has analysed the current status of medical physics education and training in several countries from Central/Eastern Europe. The results show significant increase of medical physicists in this part of the world. It is also shown that the need of such professionals in healthcare would require further boost of education and training.

This brief history of the development of medical physics education and training in Central/Eastern Europe is part of the celebrations of the development of medical physics in Europe, related to the 40th Anniversary of EFOMP in 2020. The history presents the fast progress in the region, starting from two educational courses (and no training), and reaching level similar to this of other countries with traditions in this field.

Most projects briefly described in the paper are covered in the book "The Pioneering of e-Learning in Medical Physics" [44], which the authors dedicated to all colleagues who took part in these projects and volunteered their contribution for the global development of medical physics.

The paper showed how important is to have models for development and to exchange expertise on international level (the two Annexes to the paper present two of the important models used for establishing educational courses and training activities). This is also well shown in the Summative papers from the IOMP Regional Organisations from Middle East, Latin America, Africa and South – East Asia (presented in the History – related Special Issues of this Journal Medical Physics International – see www.mpijournal.org).

The need to boost the profession through education and training was one of the main reasons for the initiation of the Journal Medical Physics International [43], which serves the profession since 2013 and provides open access information to all colleagues. These activities were, are and will be fundamental for the global growth of the profession and the quality of the services which medical physicists deliver to healthcare [45, 46, 47].

Acknowledgements

Being personally involved in the initiation, development and dissemination of many of the activities presented in this short description of the education and training development in the countries from Central/Eastern Europe, the author would like to thank most heartily to all colleagues who took part in the above-described projects, Workshops/Seminars and other activities.

As a profession we all acknowledge gratefully the financial support from EU, the IAEA, ICTP, IUPAP and other Institutions.

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ANNEX 1

Inter-University Education Centre ERM, Plovdiv: MSc in Medical Physics - MSc Modules Syllabi

This Annex 1 presents the outlines of the project ERM MSc modules syllabi. The development of the ERM project Curriculum and Modules syllabi was coordinated by S Tabakov. The Syllabi are presented here as an indication of the quality of the teaching programme developed in the MSc course ERM in Medical University Plovdiv during the period 1996-1997, as well as the quality of the many others courses, which used elements of this curriculum as part of their development.

The main lecturers of the respective modules are listed at the end together with the Lecture Notes. Many of these lecturers are now professors and senior specialists, some changed their affiliation, others retired and some are no longer with us. Naturally over these 20+ years the syllabi have developed to include new methods and equipment (and excluding the outdated ones). In a similar manner the teaching materials have been updated.

Module 1. Basis of Human Anatomy and Physiology

Aims:

The aim of this 3-weeks module is to present the theoretical knowledge on the structure of the human body and the basic mechanisms of its function.

Objectives:

Having successfully completed the module, the student should have the basic knowledge on the structure of each principal functional system of the body and to understand how do the organs work separately and as integrated units into the body. The student should obtain scientific information on the principal instrumental methods for studying human structure and for investigating the function of human organs and functional systems, their physical basis and clinical importance, the possible sources of error and artefacts which depend mainly on the human organism.

Learning Program:

The module 'Basis of Human Anatomy and Physiology' consists of 9 submodules. Each of them concerns one of the basic structural and functional systems of the human being: structure and function of the cell (in health & disease); nervous system; muscle and skeletal tissues; heart and circulation; blood and lymph; respiratory system; gastrointestinal system; urinary system; and endocrine system. A detailed syllabus for the course is attached.

Syllabus Outline

* The cell - physical structure and functional systems of the cell. Genetic control of the cell function and cell reproduction. Genetic diseases.

* Cellular injury, apoptosis, cellular death, neoplasia.

* Functional systems of the human body, biocybernetics; homeostasis. Human and cell metabolism.

* Extracellular transport of fluids and nutrients - diffusion and active transport.

* The control systems of the body (basic principles of control systems; control mechanisms and automaticity of the body).

* The nerve cell - structure and basic functions. Electrical phenomena in the nerve cell. Ionic basis of excitation and conduction. Basic physics of membrane potentials (resting membrane potential, the nerve action potential and after potentials).

* The nerve trunks; velocity of conduction in nerve fibres; inhibition of excitability (local anesthetics); recording membrane potentials and action potentials; electroneurograme; glia.

* The synapses - structure of synapses; electrical events at synapses.

* Anatomy of the central and peripheral nervous system. Anatomy of autonomic nervous system.

* Physiology of processing information in the central nervous system. reflexes (integrative function of the nervous system).

* Anatomy and physiology of the organs of sensations (cutaneus, deep and visceral sensation, pain, vision, hearing and equilibrium, smell and taste).

* Motor functions of the nervous system. Higher functions of the nervous system (leaning and memory). Behavioural and emotional functions of the nervous system. Electroencephalography.

* Skeletal muscle - physiological anatomy of skeletal muscle and skeletal muscle fibre.

* Molecular mechanism of muscle contraction. Muscle hypertrophy; muscle atrophy and electrical stimulation of skeletal muscle. Electromyography.

* The smooth muscle (physiological anatomy). Contractile process in the smooth muscle (membrane potentials in smooth muscle and excitation contraction coupling; automaticity).

* Skeletal tissues: Macroscopic and microscopic structure of the bone, tendons and ligaments.

* Skeletal tissues: Mechanism of calcification and development of the bone.

* Skeletal tissues: Diseases of the bone (osteoporosis, Paget's disease, rickets, osteomalacia, osteomyelitis, sarcoma).

* Anatomy of the heart muscle. Action potentials in cardiac muscle. Contraction of cardiac muscle. Rhythmic excitation of the heart - the especial excitatory and conductive system. Structure and function of heart valves. The cardiac cycle. Normal heart sounds. Phonocardiography.

* Regulation of the heart function. cardiac insufficiency.

* Electrocardiography. Echocardiography. Other methods for studying the structure and the function of the heart.

* Anatomy of the system circulation. Hemodynamics. Arterial pressure and its control. Arterial pulses and pressure pulses in the veins. Sphigmography and phlebography. Cardiac output and venous return.

* Physiologic anatomy of the pulmonary circulation. Pressure of the pulmonary system. Circulation trough special regions.

* Methods for studying the circulation plethismography, capillaroscopy, oscillography. The circulatory insufficiency - shock.

* Red blood cells - anatomy of the red blood cell. Normal values for the number of the red blood cells and methods for counting. Haemoglobin. White blood cells - general characteristics and morphology; properties and function. Normal values for the number of white blood cells. Immunity and allergy. Blood groups. Transfusion.

* Thrombocytes. Hemostasis and blood coagulation. Blood coagulation tests. The lymph.

* Blood disease.

* Functional anatomy of the respiration system and structure of the airways. Pulmonary ventilation and alveolar ventilation.

* Gaseous exchange - physical principles. transport of oxygen and carbon dioxide in the blood. Respiratory exchange ratio. regulation of respiration.

* The pulmonary volumes. and capacities-spirometry; methods for measuring the gaseous exchange and blood gases in humans. respiratory insufficiency.

* Anatomy of the gastrointestinal system.

* Movement of food through the alimentary tract. Secretory function of the alimentary tract. Digestion and absorption. The liver. Methods for studying the function of gastrointestinal tract.

* Nutrition and dietary basis.

* Anatomy of the kidney and the urinary tract and basic theory of nephron function. Renal blood flow through the kidneys. Glomerular filtration. Reabsorption and secretion in the tubules. Micturition.

* Methods for studying the function of the urinary system. Renal insufficiency.

* Anatomy of the endocrine glands. Nature of hormone. measurement of hormone concentrations in the blood.

* The hypothalamus as a gland. The pituitary hormones, the thyroid hormones and parathyroid hormone, the adrenocortical hormones, the pancreatic hormones.

* Reproductive and hormonal functions of the male. The female hormones. Pregnancy and lactation.

* Fetal and neonatal physiology. Methods for studying glandular function and structure.

Additional Teaching Materials to the Course Lecture Notes:

Ganong, W. F. Review of Medical Physiology., Lange Medical Publ., Los Altos, 18th ed., 1995

Greenspan, K.700 Multiple-choice Questions with Explanatory Answers (Physiology)., Prentice-Hall Int., 1990.

Guyton, A. C. Textbook of Medical Physiology., WB Saunders Co., Philadelphia, 9th ed., 1995.

McMinn’s Interactive Clinical Anatomy, Mosby, London, 1997.

Tortora, G. Introduction to the Human Body., Biol. Sci. Textbooks Inc., 4th ed., 1997.

Vander, A. J., J. H. Sherman, D. S. Luciano. Human Physiology - The mechanisms of body function., Mcgraw-Hill Inc., New York, 1994.

Laboratory equipment:

Myograph, EEG and ECG equipment, HP - multifucntional patient equipment, equipment for studying the function of the respiratory system, equipment for studying the blood.

Hours:

The module consist of 90 hours teaching of which there are 72 hours lectures, 6 hours seminars, and 6 hours of practical work. In addition 6 hours tests are included.

Links with Other Modules:

Provides basic information for Modules 4, 5, 6, 7, 8, and 9.

Student Assessment: Three tests during module delivery.

Module 2. Radiation Physics

Aims:

The course aims to present the theoretical and practical foundations for a new physics and/or engineering recruit to the basics of radiation physics.

Objectives:

Having completed the module, the student should have all necessary knowledge about ionizing radiation, its sources, its characteristics and also about the ways in which this radiation interacts with the matter and the effect it causes. He will gain some practical experience on the work with radioactive sources and on the measurements of their basic characteristics.

Learning Program:

The course is divided into six sub-modules. The first covers the radiation from atoms and molecules. X-ray radiation and its physical features are thoroughly explained. Sub-module two describes the phenomena radioactivity. Emphasis is placed on different radioactive decays, on gamma-radiation and on physical laws governing them. Sub-module 3 covers the sources of nuclear radiation and their practical applications while sub-module 4 deals with different nuclear reaction and the techniques for production of radionuclides. The last two sub-modules explain the interaction of the ionizing radiation with the matter and the effects which appear in it as a result of the interaction.

Syllabus Outline

* Atomic spectra. Bohr’s model of the atom.

* Quantum model of the atom and the molecule.

* Quantum theory of the atomic radiation

* X-ray radiation - general physical features

* Radioactive decay - general features. Radioactive theory. Radioactive series.

* Alpha and Beta radioactivity. Gamma radiation.

* Gamma radiation.

* Isotope sources.

* Nuclear reactors

* Accelerators

* General information on nuclear reactions

* Reactions with charged particles

* Photonuclear reactions.

* Neutron reactions.

* Production of radionuclides.

* Interaction of charged particles with matter.

* Interaction of X-rays and □-rays with the matter.

* Interactions of neutrons with the matter.

* Effect of the radiation on the structure of the matter.

* Chemical effects.

* Biological effects.

* Dosimetry and radiation protection - fundamentals, definitions, parameters.

Additional Teaching Materials to the Course Lecture Notes:

K. S. Krane, Introductory Nuclear Physics, John Wiley&Sons, New York, 1988

R. Chandra, , Introductory Physics of Nuclear Medicine, Lea&Febidger, Philadelphia

F. J. Blatt, Modern Physics, Mc-GRAW HILL, Inc., 1992

Glenn F. Knoll, “Radiation Detection and Measurement”, 2nd edition, John Willey & Sons - New York

D. G. Giancoli, Physics, principles with applications, Prentice Hall, Inc. 1980

Laboratory Equipment:

All the equipment in the laboratories of the Chair “Atomic Physics” at Plovdiv University will be accessible for the students.

Hours:

The module consists of 37 hours lectures, 33 hours practical work and 10 hours seminars. 10 hours of tests are also included, so that the course requires 90 hours to complete.

Links with other Modules:

Provides information for modules: 3, 4, 7 and 8.

Student Assessment: Five tests during module delivery and unseen written exam after the module.

Module 3. Radiation Measurement

Aims:

The aim of this three-weeks module is to present the theoretical and practical foundations for a new physics and/or engineering recruit to the field of radiation measurements.

Objectives:

Having completed the course, the student should have the knowledge and the practical skills required to plan radiation measurement experiment and to assemble apparatus for such experiment. The student should know the sources of possible errors, and on this base should be able to estimate the physical and technical limitations to the accuracy in a given measurement.

Learning Program:

The module is divided into three sub-modules. The first gives introduction to the field, common things for all the detectors and measurements procedures are covered there. Sub-module 2 describes a wide range of detectors. The underlying physics for each detector is explained The applications to which each detector can be put are discussed. The last sub-module covers the electronic devices, which are most commonly used with radiation detectors.

Syllabus Outline

* Detectors. General features. Classification. Modes of operation.

* Influence of the statistical processes on the radiation measurements. Basic characteristics of the detectors. Requirements for the bias supply.

* Gas-filled detectors. General description. Typical voltage dependence of a gas-filled detector.

* Ionization chambers. DC chambers. Pulse ionization chambers. Pulse shapes in ionization chambers. Applications.

* Proportional counters. Gas multiplication. Proportional counter gases. Energy dependence of the proportional counter efficiency. Multi-wire proportional chambers. Applications.

* Geiger counters. Mechanism of pulse formation. Geiger counter plateau. Count rate limitations with Geiger counters. Efficiency. Applications.

* Semiconductor detectors. Basic principles of semiconductor physics. PN junction. Principles of action of semiconductor detectors. Characteristics and parameters. Classification. Applications.

* Radio-fluorescent detectors. principles of operation. Inorganic and organic scintillators. The photomultiplier device. Construction of a scintillation counter. Thermoluminiscent detectors. Applications.

* Miscellaneous detectors. Cherenkov detectors. Special detectors using noble gases. Detectors with event storage properties. calorimetric detectors.

* Amplification principles for radiation detectors. Pre-amplifiers- voltage-, charge- and current-sensitive.

* Main amplifiers - functions, resistance-capacitance shaping, pole-zero cancellation, baseline restoration.

* Single channel analyser (SCA) and discriminator. Scalars and rate-meters. Energy spectra processing.

* Multi-channel analysers. Analogue-to-digital converters. Spectrum storage and analysis.

* Timing systems. Cables and impedance matching. Fast amplifiers. Timing windows. Time to amplitude converters. Pulse shape discriminators.

* Coincidence units. Housing of electronic units. High-voltage power supply. Complete system.

* High voltage high power rectifier.

Additional Teaching Materials to the Course Lecture Notes:

Radiation Detection and Measurement, Glenn F. Knoll, 2nd edition, John Willey & Sons - New York

Radiation Detectors, C. F. G. Delaney and E. C. Finch, 1992; Caldron Press -Oxford

EG&G ORTEC, Instruments and Systems for Nuclear Spectroscopy, Handbook, 1993/94

CANBERA NUCLEAR, Edition Nine, Instruments Catalog

Laboratory Equipment:

Different gas filed detectors, scintillation probes, semiconductor detectors, SCA, MCA, counters, spectrum analysers, computers, oscilloscopes, coincidence units, base line restorers, high voltage power supplies etc.

Hours:

The module consists of 84 hours lectures, 26 hours practical work and 7 hours seminars. 6 hours of tests are also included.

Links with other modules:

a) Requires core information: Module 2

b) Provides information for modules: 7,.8, 10.

Student Assessment: Three tests during module delivery and unseen written exam after the module.

Module 4. Radiobiology

Aims:

The aim of this two-weeks module is to provide basic knowledge in radiobiology in respect to radiobiological basis of radiotherapy with special emphasis on the aspects which are of particular importance for medical physicists.

Objectives:

Having successfully completed the module, the student should:

- Be familiar with the basic radiochemical changes in biomatter and their importance for the biological effects of ionising radiation

- Understand how variations in proliferation kinetics parameters of cell populations may affect tumour and normal tissue response to irradiation

- Be able to interpret cell survival curves and major mathematical models with respect to radiotherapy of tumours

- Be able to discuss the main types of radiation cell damage and repair and their dependence on LET, 02 tension, dose, dose rate and fractionation pattern

- Be familiar with the man pathological changes in acutely and late-responding tissues, the concept of Therapeutic ratio and Tolerance doses

- Be able to discuss the impact of dose rate and fractionation on the Therapeutic ratio

- Have a general knowledge of the principal methods of radiosensitivity modification

Learning Programme:

The module covers the following general areas in Radiobiology:

1. Introduction; 2. Radiation Chemistry; 3. Proliferation Kinetics of Cell Populations; 4. Radiation Effects on Cel; 5. Radiation Response of Tumours; 6. Radiation Effects in Man; 7. Radiobiological problems in radiation therapy; 8. Developments in Radiotherapy

Syllabus Outline

* Introduction: History and definitions.

* Radiation Chemistry.

* Proliferation Kinetics of Cell Populations.

* Radiation Effects on Cell.

* Radiation Response of Tumours: Proliferation kinetics of tumours, Post-irradiation kinetics, The four R's of radiobiology and their implication in radiotherapy.

* Radiation Effects in Man.

* Radiobiological problems in radiation therapy: Acute and late responding tissues, Therapeutic ratio, Toleranse doses, The concept of NSD, Fractionated radiotherapy, Protracted radiotherapy, Whole body irradiation.

* Developments in Radiotherapy: Radiobiological problems of high-LET radiation, Radiosensitizers and radioprotectors, Hyperthermia.

Additional Teaching Materials to the Course Lecture Notes:

Principles and Practise of Radiation Oncology, Perec C, 1992

Radiobiology for the Radiologists, Hall, E, 1988

Elements of Radiobiology, Selman J, 1983

Biological Effects of Radiation, Coggle J E, 1983

Hours:

The module consists of 40 lectures, 14 hours practical work and seminars and 6 hours tests.

Links with other Modules:

Radiobiology is the biological basis of radiotherapy - Module 8.

Student Assessment: Three tests during module delivery.

Module 5. Non-ionization Medical Imaging - Physics and Equipment

Aims:

The aim of this 3-weeks module is to present to the students the theoretical and practical bases of ultrasonic, laser and nuclear magnetic resonance instrumentation and their medical applications.

Objectives:

Having completed the module the students should gain knowledge on the basic physical and engineering principles of operation of the corresponding instruments and systems. They will be able to operate ultrasonic and laser equipment and understand the main functional control organs of magnetic resonance imaging systems.

They will also be aware of the corresponding safety requirements and rules of adequate and safe operation. The basic principles for quality monitoring and testing will be mastered including basics on servicing.

Learning Program:

The module is divided into three main submodules. The first is dedicated to ultrasonic diagnostic instruments and systems. It covers physical, engineering and medical fundamentals and practical bases in this field. The second module is structured in a similar way for laser radiation generation and medical applications. The third is centred predominantly on the basic principles. as the nuclear magnetic resonance imaging systems presently in use are of various design and operational controls with different computers.

Syllabus Outline

Ultrasonic Medical Diagnostic Instrumentation

* Ultrasound (US) - basic physical principles.

* Generation and detection of ultrasound.

* Amplitude scanning and visualisation: A-scan.

* B-mode and M-mode scanning and visualisation.

* Electronic linear and phased array scanning. Formation of a beam from a group of crystals. Basics of phase control in scanning.

* Transducers for different scanning systems.

* Computerized ultrasonic instrumentation.

* Ultrasonic image processing.

* Ultrasonic image recording on different carriers.

* Instrumentation performance testing, quality control.

* Artefacts in medical ultra-sonography.

* Doppler effect - basic notions.

* Method of pulsed (gated) Doppler for blood flow detection and measurement.

* Duplex (simultaneous) B-scan and Doppler visualisation.

* Method and instrumentation for colour flow mapping.

* New developments in medical ultrasonics.

* Basics on biological safety of ultrasound.

Lasers, Medical Applications

I. Laser radiation. Major characteristics and techniques and apparatus for measurement.

* Description of laser radiation as electromagnetic wave: polarisation, coherence - temporal and spatial structure of the laser beam. Divergence.

* Intensity and power of light, pulse energy and pulse power, average energy and average power, power density. Spectral characteristics of monochromatic laser radiation.

* Measurement of power and energy of radiation. Measurement of temporal parameters of radiation. Investigation of polarisation and spectral characteristics.

II. Absorption and emission of light. Generation of laser emission.

* Energy levels in quantum systems. Spontaneous and induced transitions between levels. Emission and absorption of light. Non-emission transitions. Stimulated emission.

* Possibilities for light amplification. Inverse population. Methods for creating of inverse population. Active media for lasers.

* Optical resonators. Losses in optical resonators. Stable and unstable optical resonators. Inverse population medium in an optical resonator. Gain, feedback, laser generation and threshold.

* Principle construction of laser. Review of laser sources.

III. Lasers for biomedical application. Action, construction, problems.

A. Lasers with optical pumping.

* Neodimium-YAG lasers.

* Q-switched Neodimium-YAG lasers

* Frequency conversion of the Neodimium-YAG laser light.

* Continuous-wave, flashlamp-pumped and pulsed-laser-pumped dye lasers. Titanium-sapphire lasers. Operation, construction and tuning.

B. Gas discharge lasers

* He-Ne lasers - construction, operation. Argon-ion lasers and crypton-ion lasers - operation, construction.

* Carbon dioxide lasers. Continuous wave CO2 lasers - construction, operation. Pulsed CO2 lasers.

* Eximer lasers - construction, operation. Nitrogen lasers. Copper vapour lasers - construction, operation. Golden laser. He-Cd lasers.

* Semiconductor-diode lasers. Types, operation, construction, spectral range and tuning. Free-electron lasers.

* The laser as a research tool in biology.

* The laser as a clinical tool.

* Sources of ultraviolet radiation. Medical applications of ultraviolet radiation. Evaluation of ultraviolet radiation in hospitals.

* Principles of fibre optics. Optical fibres in medicine. Laser safety in hospitals and research establishments.

Nuclear Magnetic Resonance Instrumentation

* Basic Physics of Nuclear Magnetic Resonance

* Basis of NMR Image formation

* Pulse sequencing in NMR Imaging

* Relaxation processes and their measurement

* NMR Image acquisition and reconstruction

* Brightness and Contrast in NMR imaging

* Instrumentation for NMR Imaging

* Biological effects and hazards of NMR

* NMR Spectroscopy

* NMR Flow imaging

Additional Teaching Materials to the Course Lecture Notes:

- Wells P. N. T. Biomedical Ultrasonics. Academic Press, 1977.

- Kissle J., Adams D. B. and Belkin R. N. Doppler Color Flow Imaging. Churchill Livingstone, 1988.

- Evans D. H., McDicken W. N. Skidmore R. and Woodcock J. P. Doppler Ultrasound: Physics, Instrumentation and Clinical Applications. Wiley Books, 1989.

- Kremkau F. W. Diagnostic Ultrasound - Principles, Instruments and Exercises. W. B. Saunders, 3rd ed., 1989.

- Fish P. Physics and Instrumentation of Diagnostic Medical Ultrasound. John Wiley & Sons, 1990.

- Hedrick W. R., Hykes D. LK. and Starchman D. E. Ultrasound Physics and Instrumentation. Mosby, 3rd ed., 1994.

Nenchev M. and Saltiel S. Laser Technique. Ed. Sofia University and Nauka i Izkustvo, 1994 (in bulgarian).

- Yariv A. Quantum Electronics. John Wiley & Sons, New York, 3rd ed. 1988.

- Milonni P. W. and Eberly J. H. Lasers. John Wiley & Sons, New York, 1988

- Arecchi F. T. and Shulz-Dubois E. O. (Eds). Laser Handbook, Vol. 1 and 2. North-Holland, Amsterdam, 1988.

- Wilson J. and Hawkes J. F. B. Lasers. Principles and Applications. Prentice Hall. New York, 1987.

- Demtroder W. Laser Spectroscopy. Springer, 2nd enlarged ed., 1995

- Law J. and Haggith J. W. (Eds). Practical Aspects of Non-Ionising Radiation Protection. Proc. Joint Meeting Hosp. Phys. Assoc., Leeds, June 1981.

- Diffey B. L. and Langley F. C. Evaluation of Ultraviolet Radiation Hazards in Hospitals. The Institute of Physical Science in Medicine, Report No. 49, 1986.

- Serafenitides A. A. Short Pulse Beam Interaction with Polymers Biocompatible Materials and Tissue. Invited Lecture. To be published in Proceedings of SPIE, 9th Internat. School on Quantum Electronics, Varna, 16-22 Sept. 1996.

- Sliney D. H. and Trokel S. L. Medical Lasers and Their Safe Use. Springer, New York, 1993.

- Carruth J. S. and McKenzie A. L. Medical Lasers (Science and Clinical Practice). (Series Editor K. Mould) Adam Hilger, London, 1994.

- Webb S. Physics of Medical Imaging, IOP Publishing, 1988

- Krestel E. Medical Imaging Systems, SIEMENS Publishing, 1988

Laboratory instruments for practical training in ultrasonics and lasers:

Modern ultrasonic scanners and nuclear magnetic resonance imaging systems will be available for demo practical on site - in the corresponding medical diagnostic departments.

Hours:

The module consist of 50 hours lectures, 34 hours seminars and practical work. In addition 6 hours tests are included.

Student Assessment: Three tests during module delivery and unseen written exam after the test.

Module 6. Diagnostic Radiology - Physics and Equipment

Aims:

The aim of this 3 weeks module is to present to the students the basic physical principles of Diagnostic Radiology. X-ray physics and principles of radiography are considered together with the aspects of X-ray engineering and maintenance. Special attention is given to the Quality Control in Diagnostic Radiology. The most important medical applications are reviewed in brief.

Objectives:

With completion of this course the students will have gained knowledge on the basic physical and engineering principles of operation of the Equipment for Diagnostic Radiology (DR). They will be able to operate DR equipment and perform DR Quality Control tests. They will also understand the basic principles of X-ray radiography and digital principles corresponding safety requirements and rules of adequate and safe operation. The basic principles for quality monitoring and testing will be mastered including basics on servicing.

Learning Program:

The course is divided into two submodules - X-ray tubes and generators (including radiography X-ray films and laboratory); X-ray Image Intensifiers and Digital X-ray systems (including X-ray TV components, Computed Tomography, Image quality assessment and patient dosimetry). All questions include elements of practical use in medicine and Quality Control.

Syllabus Outline:

* Introduction. Historical development. Basic methods of Diagnostic Radiology (DR). Types of DR Equipment.

* Formation of the X-ray image. Contrast, Brightness and Resolution in DR imaging. Contrast media. Characteristic features of the "Ray-image".

* X-ray tube - Elements. Anode, Cathode, Grids, Glass envelope, Housing.

* General Types X-ray tubes. Fundamentals of X-ray tubes assessment.

* X-ray tube Basic Characteristics, Parameters and standards.

* Classical High voltage X-ray generator. Elements, Construction and Basic Types. Safety issues.

* Basic electric circuitries of the classical HV generator. Medium frequency HV generators.

* HV - working regimes and generator parameters. Fundamentals of HV generator assessment.

* Radiographic film - Basic types, Characteristics. Radiographic screens - Basic types, Characteristics.

* General types and Basic elements of the Radiographic Equipment. Systems for Automatic Exposure Control in DR.

* Mammographic X-ray equipment. Tomographic X-ray equipment.

* X-ray Laboratory - parameters and standards of X-ray film processing.

* X-ray Image Intensifier - Components, Construction.

* Image Intensifier - Basic types and Characteristics. TV cameras and systems used in DR - basic types and characteristics.

* General types and basic elements of the Fluoroscopic DR equipment. Systems for Automatic Brightness Control in DR.

* Digitisation of fluoroscopic X-ray image. Basic types of ADC in DR. Basic parameters of the digital X-ray image. Window technique.

* Digital fluoroscopic X-ray equipment - basic types and characteristics. Digital Subtraction Angiography Equipment.

* Fundamentals of image reconstruction from projections

* CT scanners - construction and basic types.

* CT scanners - basic scanning and imaging parameters.

* Spatial resolution in DR imaging - comparison in different modes, assessment. The MTF concept. Test Objects.

* Noise in DR imaging-sources, influence, comparison in different modes, assessment. Anti-scatter grids.

* Contrast in DR imaging - comparison in different modes, assessment. Test objects.

* Post-processing of radiographs. 3D imaging in DR. Artefacts in DR imaging. Image archiving in DR and PACS architecture.

* Basic methods of Radiographic/Fluoroscopic/Digital DR practice.

* Concepts of Quality Control in DR. Patient doses comparison.

Additional Teaching Materials to the Course Lecture Notes:

Webb S. Physics of Medical Imaging, IOP Publishing, 1988

Krestel E. Medical Imaging Systems, SIEMENS Publishing, 1988

Forster E. Equipment for Diagnostic Radiology, MTP Press, 1993

Tortoricci M, Medical Radiographic Imaging, W.Saunders Co, 1992

Weir. J., P. Abrahams Imaging Atlas, MOSBY Multimedia, 1997

Simulations with PC and Multimedia are included in the module as well.

Laboratory instruments for practical training in Diagnostic Radiology:

Modern X-ray equipment, CT scanner and DSA systems will be available for demonstrations on site - in the corresponding medical diagnostic departments.

Hours:

The module consists of 78 academic hours, including 52 hours of lectures, 22 hours of seminars and practical exercises and 4 hours for tests.

Links with other Modules:

This module provides information for modules 2, 9, 10 and 11.

Student Assessment: Two tests during module delivery and unseen written exam after the module.

Module 7: Nuclear Medicine - Physics and Equipment

Aims:

The aim of this three-weeks module is to present the theoretical and practical foundation for a new physics/engineering recruit to the field of nuclear medicine.

Objectives:

Having successfully completed the course, the student should have the knowledge and skills required to provide scientific and technical support for scintillation probe systems, well counters, dose calibrators, radioimmunoassay (RIA) instrumentation, gamma cameras and associated computing equipment, including their Quality Control. The student should also understand the clinical foundation for common Nuclear Medicine studies as well as their implementation in clinical practice, such studies include in-vitro and in-vivo measurements of body function, RIA, two and three dimensional imaging. The student should know the common sources of error and artefact in all of these applications, the physical limitations to the accuracy of measurement, and the specifications required for state-of-the-art equipment.

Learning Program:

The course is divided into six sub-modules. The first gives a broad based introduction to the field while the following two address in-vitro counting systems sub-module 2 stresses physical measurements while sub module 3 focuses on clinical and laboratory measurements. The remaining sub modules address in vivo studies: sub module 4 covers scintillation probe studies while the last two focus on two dimensional and three dimensional imaging respectively. A detailed syllabus for the course is attached.

Syllabus Outline

* Contribution of Nuclear Medicine to Clinical Practice: history: current status.

* Radioisotopes used in Nuclear Medicine Production: Physical Characteristics & Implications for patient dose and image quality/assay accuracy.

* Radiopharmaceuticals: In-vivo Distribution & Kinetics: Quality Assurance Radiation Protection in Nuclear Medicine. Design of Facilities: Good Practice: Dose Optimisation

* Single probe scintillation Counting Systems: Technology and Functional Characterisation.

* Sample Assay using Well Counters and Dose Calibrators: Techniques: Sources of Error, Quality Assurance.

* Body Composition and Tissue Volume measurements

* Radioimmuno Assay (RIA): General Principles & Instrumentation

* Liquid Scintillation Counter (LSC): Principles & Technical Factors

* Data Processing in RIA

* In-Vivo Measurements with 1, 2 or 3 probe systems: General Principles and Clinical Applications.

* Linear Scanning systems: Technology and Functional Performance

* Gamma camera (a): General Principles & Construction

* Gamma Camera (b): Collimators: Design and Performance

* Gamma Camera (c): Sources of error: Functional Specification: Q.A

* Gamma Camera (d): Data Acquisition & Image Quality Measurements.

* Gamma Camera (e) Data Processing for static Images: Techniques: Clinical Implementation.

* Gamma Camera (f) Dynamic Studies: Data Processing: Clinical Implementation.

* Gamma Camera (g) Functional Imaging: Techniques: Clinical Implementation.

* SPECT (a): Basic Principles: Clinical Rationale & Technical Implementation.

* SPECT (b): Data Acquisition and Reconstruction; Sources of Error.

* SPECT (c): Image Quality: Technical Specifications for SPECT systems; QC & Acceptance Testing.

* PET: Basic Principles: Technical Implementation and Image Quality.

Additional Teaching Materials to the Course Lecture Notes:

Physics in Nuclear Medicine, J. A Sorenson & M.E Phelps 2nd Edition, 1987, W.B Saunders Company Philadelphia.

Principles and Practice of Nuclear Medicine, P.J Early & D.B Sodee 2nd Edition 1995, Mosby, St Louis

Quality Standards in Nuclear Medicine G.C Hart and A.H Smith (Editors) 1992 The Institute of Physical Sciences in Medicine. York

Laboratory Equipment:

Scintillation probes, well counter & spectrum analyser: radionucleid dose calibrator & area dose monitoring equipment: multiple sample counter; gamma camera and computer; Tc99m generator. Associated QA equipment for these instruments..

Hours:

The module consists of 72 hours teaching of which there are 42 hours lectures, 28 hours of practical work and seminars. In addition 8 hours of tests are included.

Links with other Modules:

(a) Required core information: Modules 1,2,3,4

(b) Provides information for Modules 9,10

Student Assessment:

Three tests during module delivery and unseen written exam after the end of the module.

Module 8. Radiotherapy - Physics and Equipment

Aims:

The aim of this three-weeks module is to present the physical rationale for the clinical radiotherapy, the main features and characteristics of the radiotherapy equipment and to provide dosimetric methods and physical procedures of quality assurance.

Objectives:

Having completed the module the student should gain knowledge and practical skills required to routine calibration of the treatment units, to carry out simple treatment planning, to calculate treatment time or monitor units in simple plan, to perform Quality Assurance Procedures for treatment units.

Learning Program:

The module is divided to three submodules: the description of radiotherapy equipment and sources, the electron and photon beams characteristics, the methods of ionizing radiation dosimetry, the treatment planning in radiotherapy.

Syllabus Outline

* Kilovoltage units: Operating characteristics, Grenz-Ray and contact therapy units, Superficial Therapy units, Orthovoltage Therapy units, Surface output, Beam quality, Depth dose data, Factors influencing percentage depth dose values, Isodose curves.

* Cobalt 60 units: Source and source housing, Beam collimation and penumbra, Timer.

* Linear accelerator: Principles of operation, Beam transport system, Target/flattening filter, Scattering foil, Scanning electron beam, Beam monitor, Collimation, Gantry.

* Treatment simulation and verification: Simulators, Port films, Electronic portal imaging.

* Quality of X-ray beams: Half-value layer, Filters, Measurement of Beam Quality Parameters, Factors influencing quality.

* Electron Beam Characteristics: Most Probable Energy, Mean Energy, Energy at Depth.

* Measurements of absorbed dose: Absorbed Dose, Kerma, Exposure, Relationship between Kerma, Exposure and Absorbed Dose, Calculation of Absorbed Dose from Exposure, The Bragg-Gray Cavity Theory, Calibration Protocols for Megavoltage Photon and Electron Beams, Measurements of Absorbed Dose, In vivo dosimetry.

Lect. 7h

* Dose Distribution and Scatter Analysis: Phantoms, Back scatter , Percent Depth Dose, Tissue Air Ratio (TAR), Relatioship between Tissue Air Ratio and Percent Depth Dose, Tissue phantom ratio (TPR), Tissue maximum ratio (TMR), Relationship between Percent Depth Dose and TAR, TPR, TMR, Scatter Air Ratio, Scatter Phantom Ratio.

* External Beam Dosimetric Calculations: Dose Calculation Parameters, SSD Technique, Isocentric Technique, Co60 Calculations, Irregular Fields, Asymmetric Fields, Practical Calculations

* Treatment Planning: Measurements of Isodose Curves, Parameters of Isodose Curves, Wedge Filters, Combination of Radiation Fields, Isocentric Techniques, Wedge Field Techniques, Tumor Dose Specification for External Photon Beams.

* Patient Data and Setup: Acquisition of Patient Data, Corrections for Contour Irregularities, Correction for Tissue Inhomogeneities, Field Block and Shaping

* Electron Beam Therapy: Central Axis Depth Dose Curves, Isodose Curves, Field Flatness and Symmetry, Electron Beam Treatment Planning.

* Brachytherapy: Radioactive Sources, Calibration of Radioactive Sources, Calculation of Dose Distributions, Systems of Implant Dosimetry, Computer Dosimetry, Dose Specification.

* Quality Assurance: Equipment Specification, Acceptance Testing, External Beam Units, Brachytherapy Sources, Simulator, Periodic Quality Assurance

Additional Teaching Materials to the Course Lecture Notes:

.The Physics of Radiology, H.E. Johns, J. R. Cunningham, 4th edition, Charles C. Thomas

The Physics of Radiation Therapy, F. M. Khan, 2nd edition William & Wilkins

Radiation Therapy Physics, W.R. Hendee, G. S. Ibbott, 2nd edition, Mosby

Radiotherapy Physics in Practice, J.R. William, D. I. Thwaites, Oxford Press Univ.

Hours:

The module consists of 52 hours lectures, 20 hours practical work. 6 hours of tests are also included, so that the course requires 78 hours to complete.

Links with other modules:

a) Requires core information: Module 2, 3, 4.

b) Provides information for module 10.

Student Assessment:

Three tests during module delivery and unseen written exam after the end of the module.

Module 9. Signal and Image Processing in Medicine

Aims:

The aim of this two-weeks module is to present the theoretical background and application-oriented algorithms for Signal and Image Analysis.

Objectives:

Having completed the module the students should gain knowledge and practical skills required to process X-ray, nuclear and ultrasound pictures.

Learning Program:

The module is divided in two parts. Each of them consists of 2 sub-modules.The first part gives introduction to the field, which is necessary as preliminary knowledge before the education in modules 5 through 8. The submodule 9i.1, delivered after module 4, deals with some anatomical and physiological basics of the human eye, medical image media, image parameters, storing, recording and transmitting of images. The submodule 9I.2 (below), delivered during the second term, offers basic characteristics of ECG, EEG and EMG signals and methods for their acquisition, distortion suppression and recording. The second part representing the basic course consists of 2 submodules. The first submodule deals with some problems of the signal analysis. The second submodule 9.2 is devoted to the digital image processing.

Syllabus Outline

* Time domain measure of signal properties. Estimation. Correlation and covariance. Cross-correlation function.

* Fourier transform. Discrete Fourier transform. Parseval’s theorem. Time and frequency domain equivalence. Power spectrum.

* Point operations. Automatic graylevel mapping. Binarization. Varying greylevel mapping. Arithmetic operations in two images.

* Local operations. Graylevel smoothing. Emphasizing graylevel differences. Sharpening graylevel steps.

* Global operations. Two dimensional case. Spectral experiments.

* Region-oriented segmentation. Thresholding. Connectivity analysis. Feature extraction.

* Contour-oriented segmentation. Detection of contour points. contour enhancement. Linking contour points. Contour approximation.

* Hough transform. foundations.

* Morphological image processing. Binary morphological procedures. Morphological processing of greylevel images.

* Texture analysis. Foundations.

* Pattern recognition. Foundations.

* Image sequence analysis. Foundations.

Additional Teaching Materials to the Course Lecture Notes:

Bessman H. and Ph. W. Besslich (1995) 'Ad Oculos Digital Image Processing. Student Version 2.0'. Intern. Thomson Publish.

Baxes G. A. (1994) 'Digital Image Processing. Principles and applications'. John Wiley & Sons, Inc.

Challis R. E. and R. I. Kitney (1991) 'Biomedical signal processing (in four parts). Part 1 Time-domain methods'. Med. Biol. Eng. Comput., Vol. 28, 509-524.

Challis R. E. and R. I. Kitney (1991) 'Biomedical signal processing (in four parts). Part 2 The frequency transforms and their interrelationships'. Med. Biol. Eng. Comput., Vol. 29, 1-17.

Challis R. E. and R. I. Kitney (1991) 'Biomedical signal processing (in four parts). Part 3 The power spectrum and coherence function'. Med. Biol. Eng. Comput., Vol. 29, 225-241.

Dotsinsky I. A. (1996) 'Notes on ECG Preprocessing', University of Patras, Greece.

Pavlidis Th. (1982) 'Algorithms for Graphics and Image Processing'. Comp. Sci. Press, Inc.

Hours:

The module consists of 48 academic hours including

32 hours lectures, 12 hours practice and 4 hours tests.

Links with other Modules:

Provides information for modules 5 through 8.

Students Assessment:

Three test during module delivery (one for M9I and two for M9).

Module 10. Radiation Protection and Hospital Safety

Aims:

The aim of this three-weeks module is to provide basic information on hospital safety and radiation protection. It provides an understanding of and respect of recommendation relating to the safe use of ionizing and non-ionizing radiation. Specific principles concerning the protection of individuals are presented.

Objectives:

Having completed the module the student should gain knowledge and practical skills required to use safely ionizing radiation, adopting the proper methods for protection, understanding the basic principles of safety in hospitals.

Learning Program:

The module consists of two submodules. The first one deals with hospital safety, electrical safety and other aspects of hospital safety.

The second submodule reviews basic concepts in radiation protection, presents radiation units, discusses the significance of various radiation levels. Some simple calculations in radiation protection are presented. Practical aspects for users are included, in particular a review of detectors is included.

Syllabus Outline

Safety in Healthcare

* Introduction

* General healthcare and safety problems

* Manual handling

* Seating

* Display screen equipment

* Control of substances hazardous to health

* Electrical safety

Radiation Protection

* Introduction. A brief history of the human knowledge about biological effects of ionising radiation. Early development of the radiation protection recommendations. Tasks of radiation protection, basic definitions, quantities and units.

* Biological basis of radiation protection - deterministic and stochastic effects. Sources of information about effects to humans after radiation exposure - epidemiological studies and risk models.

* Philosophy of Radiation Protection. Radiation risk - a comparison to other risks. Radiation exposure from natural sources. The conceptual framework and the system of radiation protection - ALARA principle. Dose limitation system, recommended by the ICRP. International basic safety standards and other relevant publications of IAEA, CEC etc. National legislation in the field of radiation protection. National dose limitation system and radiation protection standards. Codes of practice and guidance notes.

* Radiation protection instrumentation used for radiation surveys of photon beams. Methods and instrumentation for measuring the dose from neutrons. Dose measurements in mixed radiation fields. Dosimetry of electrons. Radiation protection instrumentation used for survey of radioactive contamination of surfaces, skin, clothing. Calibration and quality assurance.

* Personnel dosimetry. Personnel dosimeters - film badges and TLD cassettes. Dose to the trunk and to the extremities - ICRU recommendations. Calibration and quality assurance. Assessment of the activity incorporated in the organism by bio-assay methods and in vivo by whole body counting systems.

* Environmental radioactivity measurements. Sampling techniques. Low-background counting systems. Gross-counting and spectrometry measurements. Gamma spectrometry by high purity germanium detectors. Measurements of radon and radon progeny in the human environment.

* Factors affecting dose to patients, staff and public. Designation of supervised and controlled radiation areas and controlling access. Patient doses in diagnostic radiology. Dose optimisation

* Protection from external radiation. Time, distance, shielding. Workload, use and occupancy factors. Shielding design for primary, scattered and leakage radiation. Barrier calculations.

* Internal radiation protection. Routes of entry, body burden and critical organs. Determination of dose from internally deposited radio-nuclides - bio-kinetic models and committed effective dose calculation. Control of contamination. Protective clothing and respiratory protection. Treatment of contaminated personnel. Estimation of internally deposited radioactivity. Accident procedures. Design of areas for work with radioactive materials. Departmental design and related subjects. Patient dose in Nuclear Medicine - dose optimisation.

* Radioactive waste and transport. Storage of radioactive waste, disposal of liquid and solid wastes. Shipping and transporting radioactive materials. Practical aspects of the use of radio-nuclides - authorisation and training.

Additional Teaching Materials to the Course Lecture Notes:

Cember H. Introduction to Health Physics, McGraw Hill, 1996

Noz M.,Maguire G., Radiation Protection in the Health Sciences, World Sc. 1995

Hours:

The course consists of 52 hours lectures, 20 hours practical work and seminars and 6 hours tests.

Links with other Modules:

Requires core information: Module 2, 3, 4, 6,7,8

Student Assessment: Three tests during module delivery.

Module 11. Information Technologies in Medicine

Aims:

The aim of this one-week module is to provide the students with information about contemporary PC technologies and their application in medical practice.

Objectives:

Having completed the module the student gain the knowledge and practical skills of using information systems (IS), based on information received from computerised patient records (CPR) - clinical status, medicines for treatment, finances envisaged for medical care, also picture archiving and communication systems (PACS). The student should understand also some approaches for integration of modern diagnostic equipment to the IS's.

Learning Program:

The module reviews the computer networks, archiving systems and storage of patient records.

Syllabus Outline

* Introduction to information systems (IS). The main building components of IS.

* Information technologies (IT). The main components of IT.

* The general medical problems, which can be solved with the application of IT.

* Computerised patient records (CPR) - basic component of IT in medicine. Information sources for the patient.

* Centralised and distributed model of CPR.

* Integrated information systems in medicine - virtual CPR.

* Integration of diagnostic equipment to the IS. Hardware and software problems, interfaces and protocols.

* An example architecture of IS in medical department, clinical laboratory, hospital. Computerised hospital.

* X-ray department - archive of the visual information.

* Highpertext in medical IS.

Additional Teaching Materials to the Course Lecture Notes:

James A. O'Brien. Management Information Systems. Second edition. International ed. 1993.

Comuterised Medical Imaging and Graphics. Vol.15, Number 2, March-April 1991.

Scott Wallece. The Computerised Patient Records. BYTE. May 1994.

Laboratory Equipment: LAN with PC , OS Windows NT and Windows 95

Hours:

The module consists of 20 hours lectures, 8 hours of practical work and 2 hours test.

Student Assessment: One test at the end of module delivery.

Module 12. European Integration

Aims:

This one-week optional module aims to convey to students essential information about the European Union, its background, institutions and ways of functioning. The module is requirement of the EU at the moment.

Objectives:

To provide students with knowledge about the development of the EU; the way its institutions such as the European Parliament and the European Commission operate; the key policy issues (internal and external) of the Union and the importance of these issues for member countries and citizens of the EU.

Syllabus Outline:

* The European Community - aims, size, structure, historical development.

* Institutions and consultative bodies of the EC.

* EC legislation. Community law and procedures. The subsidiarity principle.

* Economic policy of the EU: The common market; European monetary system; EMU

* Other elements of the EU's internal policy: agriculture; health, education, transport and communications, environment.

* EC and the wider world. Relations EC- the rest of Europe; EC-USA, EC-Japan

* Intellectual property and the EU.

* Budget and funding within the EU. Framework programmes.

Additional Teaching Materials to the Course Lecture Notes:

Roney, Alex. EC/EU Fact Book. Fourth edition. Kogan Page, 1995.

Woods, Tony et al. European Studies. Hodder & Stoughton, 1996.

Hours:

The module consists of 30 academic hours including

20 hours lectures, 8 hours seminars/practice and 2 hours test

Student Assessment: One test at the end of module delivery.

Lecture Notes, associated with the above modules

The Lecture Notes associated with the above educational modules were published by Foundation FIM XXI, Plovdiv, Bulgaria during 1999. The authors to the Lecture Notes are the main lecturers of the respective modules:

1. Basis of Human Anatomy and Physiology (part 1), N Boyadjiev, ISBN 954 9807 12 6

2. Basis of Human Anatomy and Physiology (part 2), S Kostianev, ISBN 954 9807 13 4

3. Radiation Physics, N Balabanov, M Mitrikov, ISBN 954 9807 05 3

4. Laboratory Manual on Radiation Physics, N Balabanov, M Mitrikov, ISBN 954 9807 06 1

5. Radiation Measurements (part1) - Counting Statistics. Gas filled Detectors, A Antonov, G Belev, ISBN 954 9807 02 9

6. Radiation Measurements (part2) - Scintillation Counting. Semiconductor Detectors,

A Antonov, G Belev, ISBN 954 9807 02 9

7. Radiation Measurements (part3) - Electronics for Radiation Detection, G Stoilov, ISBN 954 9807 03 7

8. Radiobiology, M Yaneva, L Michova, ISBN 954 9807 11 8

9. Non-ionising Medical Imaging - Ultrasonic Medical Instrumentation, I Daskalov, ISBN 954 9807 08 8

10. Non-ionising Medical Imaging - Lasers for Medicine, M Nentchev, E Stoykova, ISBN 954 9807 07 X

11. Non-ionising Medical Imaging - Magnetic Resonance Imaging, G Spassov, ISBN 954 9807 09 6

12. Diagnostic Radiology - Physics and Equipment, S Tabakov, A Litchev, ISBN 954 9807 17 7

13. Nuclear Medicine - Physics and Equipment, N Sheahan, P Trindev, ISBN 954 9807 01 0

14. Radiotherapy - Physics and Equipment, F Milano, E Milieva, ISBN 954 9807 10 X

15. Introduction to Signal and Image Processing, A Litchev, G Petrova, ISBN 954 9807 19 3

16. Image Processing in Medicine, I Dotsinsky, ISBN 954 9807 20 7

17. Radiation Protection and Hospital Safety (part 1), D Pressianov, P Pavlova, ISBN 954 9807 15 0

18. Protection and Hospital Safety (part 2), C Roberts, ISBN 954 9807 16 9

19. Information Technology in Medicine, G Spassov, ISBN 954 9807 18 5

20. Introduction to European Integration, V Tabakova, ISBN 954 9807 14 2

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ANNEX 2

EMERALD Training Module on Diagnostic Radiology (X-Ray) Physics/Equipment

This ANNEX 2 presents one of the EMERALD Training Curricula. The development of this Curriculum for Training in X-Ray Diagnostic Radiology (plus associated Training tasks and Image Database) was led by S Tabakov as part of the project EMERALD. This Curriculum for structured training in medical physics was made in 1997-98 (it was updated only once in 2003). Thus some tasks are now obsolete (specifically those addressing film/screen and classical tomography). However some tasks (e.g. related to of X-ray tube/Generator assessment) are still relevant and used in many countries. Some MSc courses used part of the Training tasks as laboratories.

The EMERALD Training Curriculum is given here as an example of the breadth and depth of its coverage, and as an example of structured training (all tasks were assessed by the Consortium and external IPEM experts). If this Curriculum frame is renewed (excluding old tasks and including new ones), its concept could continue to be very useful. The concept of this training and many of its training tasks are used in many LMI countries.

Each subject of the Training curriculum has an associated DR (X-ray) Task – accessible through the hyperlinks in the left window of this address: http://www.emerald2.eu/cd/Emerald2/dr_mod/index.htm

N.B. The other Curricula and Training Tasks (with associated images) for the modules:

*Nuclear Medicine (1998),

*Radiotherapy (1998),

*MRI (2003),

*Ultrasound imaging (2003),

plus the EMERALD and EMIT project teams who developed these, can be assessed through: http://www.emerald2.eu/cd/Emerald2/index.htm

Details follow in next pages, associating the Curriculum/Timetable with specific Training Tasks.

TRAINING MODULE ON DIAGNOSTIC RADIOLOGY (X-RAY) PHYSICS/EQUIPMENT

TRAINING TIMETABLE - TRAINING CURRICULUM (1998, update 2003)

No.	**Sub-module**	**Competencies (*)** Aligned with the IPEM Training Scheme – see at the end	**Days**
i	Introduction. Programme. Using the training materials and multimedia.		**1**
1	General principles of Radiation Protection in DR	General	**3**
2	General principles of DR Quality Control organisation and equipment	General	**3**
3	X-ray dosimetry and Patient dosimetry	**3,5,9,10,12,13**	**11**
4	Radiological image	**3,7,10,11,14**	**4**
5	X-ray tube and generator	**2,3,4,5,14,15,22**	**7**
6	Radiographic Equipment	**1,2,3,4,5,6,8,10,14,16**	**11**
7	~~X-ray screens/films and Laboratory~~ (removed in 2003)	**1,7,8,16**	**5**
8	Fluoroscopic Equipment	**1,2,3,7,8,10,11,14,15,16**	**10**
9	Digital Imaging and CT Equipment	**1,2,6,7,8,10,14,16**	**10**
10	Basis of shielding in Diagnostic Radiology	**16,17,18**	**5**
11	Digital Radiography and Spiral CT (Update added in 2003)		**5**
ii	Organising of the portfolio, training assessment, etc.		**4**
	Total for 4 months: 16 weeks x 5 days = 80 days ***Total****:*		***80***

No.	**Sub-module and Subject**	**Necessary materilas/arrangements**	**Competencies acquired**	Days	Comments
i	**Introduction. Programme. Using the training materials and multimedia**	PC, General acquaintances	**Introductory**	**1**	
1.x	**General principles of Radiation Protection in DR**		**Basic concepts of RP in DR**	**3**	
1.1	Core of Knowledge Course	Core of knowledge course Multimedia, Video	General RP in DR	2	The module is a DR-RP refresher
1.2	Observing a Radiation Protection audit	Rad.Prot. visit	General RP in DR	1	
2.x	**General Principles of DR Quality Control**		**Basic concepts of QC in DR**	**3**	
2.1	Observing a QC organisation and visit	QC visit	Genral QC in DR	1	
2.2	Acquainting with the use of various QC equipment	Various QC equipment Multimedia, Video	Using QC equipment	2	

No	**Sub-Module and Subject**	**Necessary Materials / Arrangements**	**Competencies Acquired**	**Days**	**Comments**
3.x	**X-ray dosimetry and patient dosimetry**		**X-ray dosimetry** ***(3, 5, 9, 10, 12 13)**	**11**	
3.1	Cross calibrate an ionisation chamber	Calibrated Dosimeter with Ion.ch. and one other	Calibrate ion.ch.	1	
3.2	Prepare and calibrate TLD chips	TLD reader and chips, X-ray equipment	Calibrate TLD ch.	2	
3.3	Visit a Personnel Monitoring Service	Arrange visit to PMS	Organisation of PMS	1	
3.4	Examine the characteristics of a DAP meter and calibrate	DAP meter, X-ray eq.	Using DAP meter	1	
3.5	Interaction of X-rays with matter Using tables with various attenuation coefficients	X-ray attenuat coef. tables Multimedia	Using tables with attn. coef. data	2	
3.6	Use software to estimate patient doses in a variety of cases; general x-ray paediatric exposures CT exposures exposures in pregnancy	Software	Using software with patient dos. data	2	
3.7	Undertake a brief patient dose survey using TLD Undertake a brief patient dose survey using a DAP meter	TLD , DAP	Practical use of TLD and DAP for patient dosimetry	2 (8)	The data will be collected for ~8 days

No.	**Sub-module and Subject**	**Necessary materilas/arrangements**	**Competencies acquired**	Days	Comments
4.x	**Radiological Image parameters**		**Understand/assess image param. in DR** ***(3,7,10,11,14)**	**4**	
4.1	Image formation in Radiography and Fluoroscopy. Inverse square law. Different magnification. Brightness and Contrast parameters. Contrast in Diagnostic Radiology. Contrast agents in DR. Contrast Scales.	General acquaintances (Radio/fluo room) Observing X-ray images (films/fluoro/MM)	Understand Contrast and Brightness in DR image	1	All practical use of X-ray rooms from No.5 can be in one day
4.2	Image Resolution and Unsharpness. Different unsharpnesses. Combined unsharpness. Quantitative assessment of image resolution. MTF. Practical assessment of MTF. Typical phantoms.	X-ray radio/fluo room; Sp.Resol. Test Objects; PC with image proc.soft.; Observing X-ray images (films/fluoro/MM)	Understand/assess spatial resolution in DR	1	Repeated in No.7&9 as part of a whole QC test
4.3	Image noise and SNR in DR. Noise assessment. Wiener spectrum. Contrast resolution. Typical phantoms.	X-ray radio/fluo room; Contr.Res. Test Objects; PC with image proc.soft.; Observing X-ray images (films/fluoro/MM)	Understand/assess cont.res. and noise in DR	1	same
4.4	Scatter Radiation and Contrast. Techniques for decreasing of Scatter radiation influence. Anti-scatter grids (construction and grid ratio). Stationary grids. Moving grids. Using of Anti-scatter grids. Errors in Using of Anti-scatter grids.	X-ray radiogr. room; Different Anti-scat. grids; Test objects; Films/cassettes	Understand/assess/use anti-scatter grids	1	More practical use of grids

No.	**Sub-module and Subject**	**Necessary materilas/arrangements**	**Competencies acquired**	Days	Comments
5.x	**X-ray tube and generator**		**Understand/measure/ compare separate X-ray tube/gen. parameters** ***(2,3,4,5,14,15,22)**	**7** tot	
5.1	X-ray tube Components. X-ray tube Characteristics. Loading diagramm of a X-ray tube. Some typical X-ray tube characteristics. Special X-ray tube types.	X-ray tube diagrams; Different company broshures; 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. diagramms; ~6 X-ray film/cassetes	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 . Assesing the beam alignement. 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 otput param., focal spot size and LBD. Learn to season the tube	2	same
5.4	Block diagramm of the X-ray Generator. Basic electrical circuitries of the HV generator. HV rectification. Electrical safety. kVp assessment with non-ivasive kVp meter. kVp waveform and ripple. kVp consistency, accuracy and variation with mA. Typical values. Other ways of kVp assessment. Timer and mA assessment. Typical values.	X-ray gen. diagrams; X-ray radiogr. room; kVp divider; kVp non-inv. meter; oscilloscope; kVp cassette; mA and Timer meters.	Understand/measure kVp with different tools. Assess ripple. Measure mA.time of the exposure	2	same

No.	**Sub-module and Subject**	**Necessary materilas/arrangements**	**Competencies acquired**	Days	Comments
6.x	**Radiographic Equipment**		**Using and QC of radiographic equip.** *** (1,2,3,4,5,6,8,10, 14,16)**	**12** tot	
6.1	General Radiography Equipment. Main features of the Control panel of a typical Radiography equipment. Practical use of Radiographic equipment. Selecting the X-ray exposure parameters (2 and 3 point systems).	General acquaintances with practice (patients) in the Radiographic room Observing radiagraphic procedures in DR	Using DR equipment; Practical selecting X-ray parameters; Patient care.	2	Observing radiographic procedures & different X-ray param. settings
6.2	Quality Control of a typical Radiography equipment. Typical QC protocol. Excel spreadsheet with QC programme. Interpretation of QC results. Additional checks in Accepting testing.	X-ray radiogr. room; Dose, kVp, etc. meters; QC protocols, PC.	Perform QC tests and QC protocols; Accept DR radiogr.eq. Interpret the QC result	2	Full QC survey (linked with experience from No.4,5,6
6.3	Specificities in QC of Mobile Radiography equipment. QC protocol for capacity discharge equipment.	Mobile X-ray radiogr. eq.; QC equipment; QC protocols, PC	Perform specific QC tests for mobile radiogr. eq. Interpret the QC result	1	same
6.4	Quality Control of Dental Radiography Equipment. Typical QC protocol. Ortho-pan Tomography Equipment - basic principles and CD tests.	Dental X-ray radiogr. eq.; QC equipment; QC protocols, PC	Perform specific QC tests and write QC protocols for Dental equipment; Interpret the QC result	2	same

6.5	Quality Control of Mammography Equipment. Typical QC protocol. Excel spreadsheet with QC programme. Interpretation of QC results.	Mammo X-ray radiogr. eq.; Special Mammo QC equip. and test objects; QC protocols, PC	Perform specific QC tests and write QC protocols for Mammo-graphic equipment; Interpret the QC result	2	same
6.6	~~Special Radiography equipment. Conventional Tomography Equipment - Specific QC checks and phantoms.~~ Task 6.6 was removed in 2003	Tomogr. X-ray radiogr. eq.; QC equipment and test objects; QC protocols, PC	Perform specific QC tests and write QC protocols for Tomo-graphic equipment; Interpret the QC result	1	same
6.7	AEC systems in Radiography. Practical using of AEC. Basic AEC parameters. Quality Control of AEC.	X-ray AEC radiogr. eq.; QC equipment, test objects; QC protocols, PC.	Use of different AEC. Perform specific QC tests and write QC protocols for AEC; Interpret the QC result	2	Observing using AEC plus full QC survey.

No	Sub Module and Subject	Necessary Materials / Arrangements	Competencies Acquired *(1,7,8,16)	Days	Comments
7.x	**X-ray films/screens and Laboratory**		**Assess X-ray films/ screens, QC in X-ray Laboratory**	**5**	
7.1	Change developer/fixer in a film processor	X-ray film processor, arrange visit during change of dev/frx	Acquaint with X-ray film processing	1	
7.2	Run a routine sensitometry strip and read the results	Sensitometer, densitometer	QC in X-ray lab.	1	
7.3	Expose films of various types/speeds and measure various parameters including characteristic curve, contrast, latitude and gradient	Different films, film character., X-ray equip., densitometer	Assessing X-ray films	2	In assoc. with 7.4
7.4	Examine response of films to various types of film screens	Different screens and films, X-ray equip., densitometer	Assessing X-ray screens	1	In assoc. with 7.3

These tasks were removed in 2003 and replaced with 3 new tasks on CD and DDR and 2 new tasks on Spiral CT

(see below - 11.x New Tasks)

No.	**Sub-module and Subject**	**Necessary materilas/arrangements**	**Competencies acquired**	Days	Comments
8.x	**Fluoroscopic Equipment**		**Using and QC of fluoroscopic equip.** **Image quality assess.** *** (1,2,3,7,8,10,11,14, 15,16)**	**10** tot	
8.1	Block diagramms of II-TV sytem and contemporary Image Intensifier. Basic components and characteristics of II. Basic TV camera types and characteristics. Assessment of the image noise. Assessment of the Spatial resolution and Contrast resolution. Video signal assessment. Typical values. Typical Contrast/Detail diagramms.	II , TV and camera diagrams; Different broshures; Oscilloscope; TV line selector; Test objects; PC	Understand/compare X-ray fluoroscopic equipment; Image quality and video signal assessment	2	Linked with experience from No.5
8.2	Typical Fluoroscopy equipment. Layout of the equipment in the room. Scatter radiation considerations. Typical control panel. Typical modes of operation of fluoroscopic equipment. Practical use of fluoroscopic equipment.	Fluoroscopic room; Dosimeter	Using fluoroscopic equipment; Practical selecting of X-ray fluoroscopic param.; (Patient care).	2	As above plus more practical use of equip.
8.3	Assessment the fluoroscopic image quality. QC equipment and phantoms. Typical QC protocol. Excel spreadsheet with QC programme. Interpretation of QC results. Additional tests in Acceptance testing. Assessment of mobile Fluoroscopic equipment.	Fluoroscopic room; mobile Fluoroscopic eq.; Test objects; QC equipment; QC protocols, PC	Perform specific QC tests and write QC protocols for Fluo-roscopic equipment; Interpret the QC result	2	As No.9.1
8.4	ABS systems in Fluoroscopy. Basic types ABS systems and parameters. Dose output/II Format dependence. Patient skin entrance dose. Quality Control of ABS. Excel spreadsheet with QC programme. Interpretation of QC results. Typical parameters.	Fluoroscopic room with ABS; Dosimeter; range of attenuators QC protocols, PC	Perform specific QC tests and write QC protocols for ABS fluorosc. equipment; Assess patient skin dose in fluoroscopy Interpret the QC result	2	

8.5	Quality Control of Angiographs. Electrical requirements for Angio rooms. Angio-acessories (Film changer and 100mm camera, Synchronisator and Cine camera). Assessing the additional imaging devices and fluoroscopic modes.	Angio-room, Test objects; Oscilloscope; QC equipment and test objects; QC protocols, PC	Perform specific QC tests and write QC protocols for Tomo-graphic equipment; Interpret the QC result	2	Experienc e with several equip. types can be of need. Linked with No.10

No.	**Sub-module and Subject**	**Necessary materilas/arrangements**	**Competencies acquired**	Days	Comments
9.x	**Digital Imaging and CT Equipment**		**Using and QC of radiographic equip.** *** (1,2,6,7,8,10,14,16)**	**10** tot	
9.1	Postprocessing of digital images. Filtering, Harmonization, Subtraction. Histogramm manipulation. Reconstruction principles. Digital image formats and compressions. Digital image parameters. Contrast and Brightness. Typical “Window techniques”.	PC. Image processing software Digital X-ray equip. (or CT console).	Image processing; Using the window technique and other built-in functions in Dig. X-ray eq./CT	2	
9.2	Formation of the digital image in DR. Typical Block Diagram of the equipment. System types. Adjusting the TV camera Gain. CCD camera.	Digital X-ray II-TV (DSA) equip. plus respective diagrams	Understand typical working modes. Adjusting camera gain	1	
9.3	DSA equipment. Practical use of DSA. Subtraction techniques. Functional imaging. Densitometry and Quantitative Cardio measurements. QC of Digital X-ray equipment. Image quality assessment. Specific test objects. Typical image quality parameters. Spatial resolution. Influence of the matrix and “processing algorithms”. Contrast resolution. Noise manipulations.	DSA eq., test objects, QC equipment, pre-recorded cardio images	Using quantitative DSA measurements. QC of DSA	2	Assoc. with 9.5
9.4	Archiving of digital images. Picture Archiving and Communication Systems.	Visiting PACS Centre	Acquaint with PACS administration	1	
9.5	CT equipment. General block diagram. CT scanner generations. Basic CT equipment componentes. Practical use of CT. Typical CT scanner installation. Room and environment requirements. General CT scan and topogramm - scanning parameters. Scanning radiation dose.	CT equipment plus respect. diagr.	Understand typical CT working modes and practice	2	
9.6	QC in Computed Tomography - typical parameters. QC protocol. Figure of merit. Interpretation of results.	CT scanner, test objects, QC equipment, prerecorded images	Using quantitative CT measurements. Perform QC of CT scanner	2	

No	**Sub-Module and Subject**	**Necessary Materials / Arrangements**	**Competencies Acquired *(16,17,18)**	**Days**	**Comments**
10.x	**Basis of shielding in Diagnostic Radiology**			**5**	
10.1	Perform shielding measurements using a variety of materials (*eg* lead, lead glass, barium plaster, ordinary plaster, x-ray tables, concrete *etc*)	Shielding materilas, dosimeter, attn.tables	Perform basic DR shielding measur.	2	
10.2	Comment on a pre-existing room plan	Room plan	Assess DR room shielding	1	
10.3	National, EU and International regulations and standards in Diagnostic Radiology	Standards, Regulations	Acquaint. with the basic rag/std docum. in the field of DR	2	The subject is taken in detail in the Rad.Prot. module

No.	**Submodule and Subject – UPDATE 2003**	Necessary Materials/Arrangements	Competencies acquired	Days	Comments
11.x	**Digital Radiography and Spiral CT**				
11.1	Testing DDR and CR Systems – Introduction and Routine Testing (Non-Image Quality)	General acquaintance CD/DDR Equipment Test objects		1	
11.2	Testing DDR and CR Systems – Qualitative Image Quality	CD/DDR Equipment		1	
11.3	Testing DDR and CR Systems – Quantitative Digital Analysis	CD/DDR Equipment		1	
11.4	Basic Principles of SPIRAL CT	General acquaintance Spiral CT equipment		1	
11.5	Quality Control of SPIRAL CT	General acquaintance Spiral CT equipment Test objects		1	

Diagnostic Radiology Competencies (as per IPEM Training Scheme)

A. Use of Equipment The trainee shall be able to:

1. B operate most types of X-ray unit for the purpose of equipment testing (complex X-ray units, CT scanners, etc may require the assistance of an experienced operator);
2. B perform measurements and test procedures appropriate to the commissioning and periodic performance testing of various types of diagnostic X-ray equipment;
3. B select and operate appropriate measuring equipment for radiation quantity in the primary beam, attenuated beam and scattered beam. (These should include ionisation chambers, geiger counters, scintillation counters and solid state devices);
4. B operate non-invasive tube voltage measuring devices;
5. B perform other basic tests such as measurement of radiographic exposure time, half value layer filtration, beam collimation, tube leakage, etc.;
6. B perform specific performance tests on specialised equipment e.g. mammography units, conventional tomography systems and CT scanners;
7. B check the imaging performance of various types of X-ray equipment, including measurement of contrast, resolution, unsharpness, noise, distortion etc. and use of appropriate test objects and test phantoms;
8. B prepare reports and draw conclusions resulting from tests and measurements on various types of diagnostic X-ray equipment.
9. C calibrate or arrange calibration of various types of test equipment for diagnostic radiology equipment.

B. Quality Assurance and Quality Control The trainee shall:

10.
B be aware of factors affecting dose to patients, staff and public;
11.
B be aware of consequences, hazards and control of scattered radiation;
12.
B be familiar with methods for measurement of patient, staff and environmental dose (including the use of TLD);
13.
B be able to calculate the dose to organs and the effective dose;
14.
B have an appreciation of the magnitude and range of dose for various X-ray procedures;
15.
B be familiar with the use of protective clothing and equipment for patients and staff,
16.
B be familiar with the designation of supervised and controlled radiation areas, appropriate systems of work and means of controlling access;
17.
B be able to calculate the required thickness of protective barriers and shields and choose appropriate types of shielding materials;

18.
B be able to measure the attenuation of protective barriers and shields;
19.
B take appropriate action in case of accidents and incidents;
20.
C supervise and perform test procedures appropriate to the commissioning and periodic performance testing of various types of diagnostic X-ray unit;
21.
C review data and reports of equipment surveys and discuss with others the findings, implications and action required;
22.
C assess equipment in terms of its safety and suitability for use;
23.
C provide guidance on routine quality control quality assurance procedures for various types of diagnostic X-ray equipment.

Legislation Guidance The trainee shall:

24.
B be able to discuss the scope and requirements of relevant national legislation.;

25.
C be able to interpret and apply existing legislation, codes of practice, guidance notes and related documents appropriate to diagnostic radiology;

26.
C be able to interpret and apply appropriate standards documents, in particular British and European standards;

27.
C be able to overview the procedures involved in the design and commissioning of new diagnostic radiology facilities;

28.
C have knowledge of alternative diagnostic techniques and modalities (such as ultrasound and MRI) for obtaining diagnostic information with particular reference to reduced radiation dose;

29.
C be thoroughly familiar with methods of dose assessment, calculation of dose and use of protective measures and be able to take appropriate action in case of incidents or accidents.

INFORMATION FOR AUTHORS

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A special feature of Medical Physics International (on line at www.mpijournal.org) is the publication of thesis and dissertation abstracts for recent graduates, specifically those receiving doctoral degrees in medical physics or closely related fields in 2010 or later. This is an opportunity for recent graduates to inform the global medical physics community about their research and special interests.

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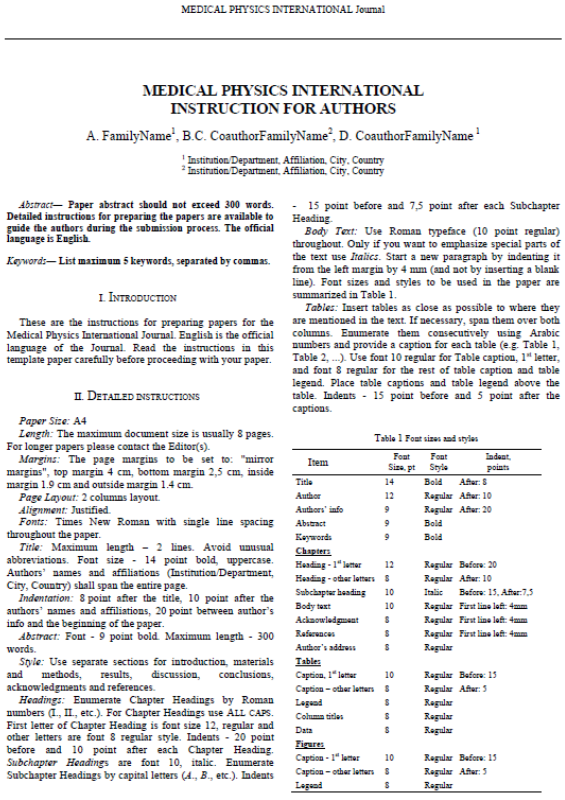

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Margins: The page margins to be set to: "mirror margins", top margin 4 cm, bottom margin 2,5 cm, inside margin 1.9 cm and outside margin 1.4 cm.
Page Layout: 2 columns layout.
Alignment: Justified.
Fonts: Times New Roman with single line spacing throughout the paper.
Title: Maximum length – 2 lines. Avoid unusual abbreviations. Font size - 14 point bold, uppercase. Authors' names and affiliations (Institution/Department, City, Country) shall span the entire page.
Indentation: 8 point after the title, 10 point after the authors' names and affiliations, 20 point between author's info and the beginning of the paper.
Abstract: Font - 9 point bold. Maximum length - 300 words.
Style: Use separate sections for introduction, materials and methods, results, discussion, conclusions, acknowledgments and references.
Headings: Enumerate Chapter Headings by Roman numbers (I., II., etc.). For Chapter Headings use ALL CAPS. First letter of Chapter Heading is font size 12, regular and other letters are font 8 regular style. Indents - 20 point before and 10 point after each Chapter Heading. *Subchapter Headings* are font 10, italic. Enumerate Subchapter Headings by capital letters (*A.*, *B.*, etc.). Indents - 15 point before and 7,5 point after each Subchapter Heading.
Body Text: Use Roman typeface (10 point regular) throughout. Only if you want to emphasize special parts of the text use *Italics*. Start a new paragraph by indenting it from the left margin by 4 mm (and not by inserting a blank line). Font sizes and styles to be used in the paper are summarized in Table 1.
Tables: Insert tables as close as possible to where they are mentioned in the text. If necessary, span them over both columns. Enumerate them consecutively using Arabic numbers and provide a caption for each table (e.g. Table 1, Table 2, ...). Use font 10 regular for Table caption, 1st letter, and font 8 regular for the rest of table caption and table legend. Place table captions and table legend above the table. Indents - 15 point before and 5 point after the captions.

Table 1 Font sizes and styles

Item	Font Size, pt	Font Style	Indent, points
Title	14	Bold	After: 8
Author	12	Regular	After: 10
Authors' info	9	Regular	After: 20
Abstract	9	Bold	
Keywords	9	Bold	
Chapters			
Heading - 1st letter	12	Regular	Before: 20
Heading - other letters	8	Regular	After: 10
Subchapter heading	10	Italic	Before: 15, After: 7.5
Body text	10	Regular	First line left: 4mm
Acknowledgment	8	Regular	First line left: 4mm
References	8	Regular	First line left: 4mm
Author's address	8	Regular	
Tables			
Caption, 1st letter	10	Regular	Before: 15
Caption – other letters	8	Regular	After: 5
Legend	8	Regular	
Column titles	8	Regular	
Data	8	Regular	
Figures			
Caption - 1st letter	10	Regular	Before: 15
Caption – other letters	8	Regular	After: 5
Legend	8	Regular	

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Figures: Insert figures where appropriate as close as possible to where they are mentioned in the text. If necessary, span them over both columns. Enumerate them consecutively using Arabic numbers and provide a caption for each figure (e.g. Fig. 1, Fig. 2, ...). Use font 10 regular for Figure caption, 1st letter, and font 8 regular for the rest of figure caption and figure legend. Place figure legend beneath figures. Indents - 15 point before and 5 point after the captions. Figures are going to be reproduced in color in the electronic versions of the Journal, but may be printed in grayscale or black & white.

Fig. 1 Medical Physics International Journal

Equations: Write the equation in equation editor. Enumerate equations consecutively using Arabic numbers

$$A + B = C \quad (1)$$

$$X = A \times e^{at} + 2lkt \quad (2)$$

Items/Bullets: In case you need to itemize parts of your text, use either bullets or numbers, as shown below:

- First item
- Second item

1. Numbered first item
2. Numbered second item

References: Use Arabic numbers in square brackets to number references in such order as they appear in the text. List them in numerical order as presented under the heading 'REFERENCES'. Examples of citations for Journal articles [1], books [2], the Digital Object Identifier (DOI) of the cited literature [3], Proceedings papers [4] and electronic publications [5].

III. CONCLUSIONS

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