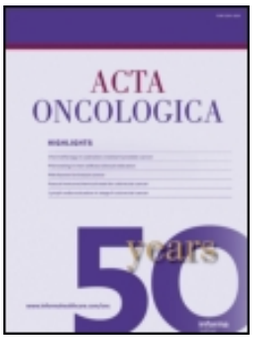

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THE RACE FOR MEGAVOLTAGE

X-rays versus telegamma

ROGER F. ROBISON

Roentgen's discovery was announced in January, 1896, and x-ray therapy trials followed in 1897. Becquerel rays and radioactive minerals were identified during 1896 through 1898. Radium was used for therapy by 1901, even though a pure standard was not achieved until 1910–1912. Quantities of radium finally became available after 1919, and for 20 years telegamma therapy machines underwent progressive development. Their megavoltage beam was much preferred over the standard 200–250 KV x-ray units of that time. Nuclear physicists during the Great Depression modified electron accelerators into giant 600–900 KV medical x-ray therapy machines and achieved one MV by 1937–1939. These were huge, complex, expensive, and unique to major academic and/or metropolitan centers. During World War II nuclear reactors superseded cyclotrons as efficient factories for new radioisotopes, including 'artificial radium'. Few seemed interested in the latter for use in telegamma therapy until 1949–1951, when three competing teams from Canada and the USA designed telecobalt machines. From this competition, among then unknown innovators, emerged three future giants in radiation therapy: A.E.C.L., H. Johns, and G.H. Fletcher. The clinical application of telecobalt therapy was to revolutionize cancer care in community hospitals worldwide.

Between 27 October and 8 November 1951, two modest-sized Canadian hospitals began treating cancer patients with 1.2 MV beams from 1 000 curie telecobalt machines (1–3). The machine used at Saskatoon Cancer Clinic in Saskatchewan, had been designed by the local physicist Harold Johns. It had been manufactured by the local Acme Machine Shop, Fig. 1. The design would later be incorporated for manufacture by the Piker Company (4).

The machine put in use in London, Ontario, at Victoria Hospital was built by a Canadian crown company known at that time as Eldorado Mining and Refining, later to be known as Atomic Energy Canada Ltd. (A.E.C.L.), and later still as Theratronics (4, 5). The design was apparently the work of a team of physicists employed in Ottawa, where the machine was tested from August to October of 1951 before being shipped to London, and put into service on 27 October (6, 7). Fig. 2 shows the Eldorado unit.

Table 1 lists the characteristics of the two machines and the scientists involved (4).

In today's world, where million-dollar linear accelerators abound in community hospitals, it may be hard to realize the positive impact that telecobalt machines generated in 1952. They brought inexpensive megavoltage therapy to non-medical center hospitals everywhere. Also, in light of the overwhelming commercial success of the Canadian machines, it is often forgotten that American oncologists were also interested in developing telecobalt units, even if their government was not. This paper reviews: 1) the historical background of teleradium therapy which made it a viable alternative to roentgen rays, 2) the American preoccupation with 'supervoltage' particle accelerators, 3) why and how the Canadian government became involved in the telecobalt business, and 4) the post World War II emergence of telecobalt as a practical cost-effective machine.

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Fig. 1. The Acme telecobalt unit.

Fig. 2. The Eldorado telecobalt unit.

Early therapy trials

Roentgen's discovery received worldwide publicity in January, 1896. The rapidity of the implementation of x-ray therapy was remarkable and the discovery could thus be put into immediate practical use because of the plentiful number of cathode ray tubes already in existence. Quickly, in January and February of 1896, the physiological effects, such as epilation and skin damage resulting from prolonged exposure, were observed and they suggested that x-rays might prove therapeutic in destroying unwanted growths of tissue, hair or microorganisms (8–16).

The first Roentgen ray tubes by Hittorf, Crookes, Lenard, and Geissler, delivered an energy of 40 to 70 KV. In 1913, the G.E. Coolidge 'hot cathode' tube operated at 140 KV. The same tubes were used for both diagnosis and therapy, and only 'hard tubes' could penetrate much beyond 1 cm. At these energies and without the full understanding of a) filtration, b) the relationship between the F.S.D. and the depth dose, and c) fractionation as opposed to massive single doses, it is not surprising that successful roentgen therapy was largely limited to dermatological conditions (17). Until the introduction of the 200 KV 'deep therapy' tube in 1922, roentgen therapy was viewed with disdain (11, 13, 18–20).

Dr. James Ewing (1866–1943), the Director at Memorial Hospital (NY, NY), in the first Janeway Lecture in 1934 described the atmosphere of x-ray therapy during 1910 to 1920 as 'quite obnoxious'. 'The noisy racket of the transformers, the noxious gases exhaled from the tubes in ill-ventilated rooms, and the retching of nauseated patients created a repulsive contrast to the solemn ceremonies of the surgical amphitheater. Patients were often burned from unexpected leaks, and on one or more occasions it is said they were actually electrocuted on the treatment table. Roentgenologists who engaged in therapy were looked upon with suspicion. It was difficult to enlist the interest of

Table 1

Canadian twins

	Acme	Eldorado
City	Saskatoon, Saskatchewan	London, Ontario
Hospital	University	Victoria
Physician	Watson, T.A.	Smith, I.H.
Design	Johns, H.E.	Green, D., Errington, R.
Physics support	Physics department at the University of Saskatchewan: Bates, L.M., Epp, E.R., Cormack, D.V., Fedoruk, S.	Radiology Lab and Physics Division of the National Research Council of Canada, Ottawa
Mounted on	Ceiling	Floor
On/Off	Motorized wheel	Mercury switch
Manufacturer	Acme Machine & Electric	Eldorado Mining & Refining
Marketed by	Piker	AECL
Dedication	23 Oct. 1951	11/12 Nov. 1951
First patient	8 Nov. 1951	27 Oct. 1951

Table 2

Radium therapy trials, 1901–1905

Year	Therapist(s)	Disease/Disorder
1901	H.A. Danlos; P. Bloch	Lupus erythemateux
1902	H.A. Danlos (Paris)	Skin cancer; port wine nevi; psoriasis; lupus vulgaris (TB)
1903	W.H. King (USA)	Optic nerve neuritis
1903	M. Cleaves (USA)	Sarcoma, cheek; cervix cancer
1904	M. Einhorn (USA)	Stomach cancer (via capsule)
1904	Rehns & Salmon	Leukoplakia
1904	F.H. Williams (USA)	42 cases
1904	Williams, Werner, Hirschell	Keloids
1904	R. Abbe (USA)	Cervix cancer
1904	Abbe, Bockoff	Warts
1904	Lassar & Abbe	Breast cancer
1904	O. Lassar (Berlin)	Eczema
1904	Hartigan	Pigmented nevi
1904	M. Metzenbaum (USA)	Lupus
1905	M. Metzenbaum	Skin cancer; rodent ulcer
1905	W.J. Morton (USA)	Sarcoma
1905	R. Abbe (USA)	Goiter; cervix; fibroids
1905	Blaschke	Sycosis; lichen ruber; eczema; acne rosacea
1910	Brussels Congress requests on International Radium Standard	
1912	March, Curie and Vienna standards agree closely	
1913	Gynecologic Congress in Germany initiates demand for mass radium as well as brachytherapy (Kronig, Gauss)	
1914	The Kaiser's War (1914–1918) restricts mass radium to USA, Baltimore MD & Memorial NY, NY	

any established roentgenologist in this questionable field' (21).

Radium teletherapy

The discovery of radium in December, 1898, was followed by years of painstaking work to chemically separate enough milligrams to obtain an accurate atomic weight. This was achieved in 1907, and in 1910 pure metal radium was prepared (22, 23). In 1912 the Vienna Radium Institute and M. Curie prepared the first International Radium Standards (24).

In 1900 two German scientists in Braunschweig had been the first to report the skin damage (Hautentzundungen) resulting from radium rays (4, 24–27). P. Curie and H. Becquerel jointly published in 1901 their experiences with personal radium burns (28). These reports led to early therapy trials with impure radium salts of varying radioactive strength. Table 2 lists some of these early workers in radium brachytherapy at this time of uncertain dosage but encouraging clinical results, 1901–1905 (17, 18, 29–32). A firm clinical foundation for radium therapy, however, had to await the acceptance of the international radium standard in 1912.

The gamma rays from radium have an average energy of about 1.0 to 1.2 MV, thus being very similar to the cobalt-60 beam (33). This quantitative superiority in energy, shorter wavelength, was not appreciated for some years. Energy was not well defined until the establishment of the 'roentgen' unit in 1928, its adoption for both gamma and x-rays in 1937, and the concept of the 'rad' in 1954 (24). However, the early clinicians did sense the superior penetration and effectiveness of radium. By the early 1920s this superiority was understood to be related to the shorter wavelength of the gamma rays. By 1923 radium rays were shown to be equivalent to two MV roentgen rays (32, 34).

Nevertheless, telegamma therapy (megavoltage) was to lag behind x-ray tube therapy (kilovoltage) until 1952. There were obvious reasons for this lag. Radium was always scarce and costly. Because of the limited availability of radium prior to 1922, its clinical use was essentially confined to brachytherapy only. Under these circumstances, curie-therapy was used in cavities and lumens, interstitially, and on the skin suface. Thus intrauterine, intravaginal, and interstitial radium was used enthusiastically for uterine cancer, a prime cause of cancer death in women from 1900 to 1945, and some breast cancers, lymph nodes, and head and neck cancers could be reached by the short wavelength (one MV energy) gamma rays from several hundred milligrams of radium placed on the skin surface (mass radium).

Table 3

Radium teletherapy units

Reported	Institution: Authors	Grams/ Curies	S.S.D. in cm	Field size in cm	Remarks: (reference No.)
1915–1923	Baltimore, MD: H. Kelly, C.F. Burnam	1.0–4.0	1–10		Radium 1913–15; radon 1918–23 (44–46)
1917	Memorial Hospital NY, NY.: H. Janeway, G. Failla	1.0–4.0	1–10		Radium 1914–16; radon 1917–19 (43)
1922	Buffalo, NY: K.W. Stenstrom	1.5 curies	6	6.5–7	Radon only; 17% of skin dose at 10 cm (9, 39, 40)
1922	Middlesex Hosp.: London, U.K., S. Russ	2.5			Portable piston; 18 month trial (24, 49)
1923	Radiumhemmet: E. Lysholm, R. Sievert	1.0–2.0	2–5	5 × 5	Channeled beam; lead protection (51)
1925	Brussels: F. Sluys, E. Kessler	1.3	6–8		13 convergent beams; ceiling mounted (4)
1925	France: L. Mallet, R. Coliez, Danne	0.3–0.6	12+		3 separate sources; floor mounted (4)
1926	Paris Institute of Radium: R. Ferroux, 0. Monod M. Bruzaz, C. Regaud	4.0	3–10	a: 14 × 14 b: 150 cm^2	Ceiling mounted. 29% of skin dose at 10 cm. (37, 62)
1928	Paris, Villejuif: S. Laborde	1.0–4.0		a: 3 × 3 b: 9 × 9	Ceiling mounted (4)
1928	Memorial Hosp. NY, NY: G. Failla	4.0	6–20	10–10	Source stored in unit head; Ceiling mounted (47)
1930–56	Westminster Hosp.: London				(37, 50)
	(a) 1930–R. Carling H. Flint, L. Grimmett	4.0	10	13 × 13	1929–32; trial × 15 mo with 4 gms
	(b) 1934–H. Flint, R. Carling, S. Cade, C. Wilson, L. Grimmett	2.0	5	3.5 × 3.5	1933–54 in service
	(c) 1938–H. Flint, C. Wilson	4.0	8	a: .5 × 3.5 b: 9.0 × 9.0	1936–53 in service
	(d) 1956–C. Wilson	10.0	11.4		1949–54 then converted to cobalt-60
1931	Brussels: M. Cheval, L. Mayer	4.0	a: 4.5 b: 6.5 c: 8.5	8 × 8	1926–? (77)
1931	Bellevue Hosp. NY, NY: I. Kaplan	5.0	6	8 × 10	1932–? (75, 76)
1933	Radiumhemmet: R. Sievert	3.0	6	a: 5 × 5 b: 7 × 7	Source transfered from head to safe. (52)
1936–37	Radium Institute London: L. Grimmett	5.0	8.3	Nozzles (cones)	Transfer by hand or pneumatic (66, 67)
1937	Radiumhemmet: R. Sievert, S. Bennen	5.0			Transfer by wire or pneumatic (53, 54, 56)
1935–40	United States, Misc.:				
	(a) 1935–Philadelphia: W. Newcomet	4.0	4–25	9 × 9	(4)
	(b) 1936–Buffalo: B. Simpson, M. Reinhard	4.5	10–15	10 × 10 fixed	Fixed 3 beams – focused 2–6 cm below skin for 80% skin dose
	(c) 1940–Los Angeles Tumor Inst.: A. Warner, R. Neil	4.0			533 r/min at 1 cm

Table 3.—(Contd.)

Reported	Institution: Authors	Grams/ Curies	S.S.D. in cm	Field size in cm	Remarks: (reference No.)
1947–49	U.K., Misc.: C. Wilson	10.0			(37, 49, 50)
1951	Royal Hospital London: C. Wilson	12.0			(50)
1954	Roosevelt Hosp. NY, NY: G. Failla, D. Quick	50.0	25	7 × 7	3 r/min at 10 cm below skin focus $25 000 a gram (on load) (48)

In 1913 Drs. B. Kronig and C.J. Gauss, at the Frauenklinik in Freiburg, Germany, aroused interest in the treatment of gynecological tumors by using, in addition to intracavitary techniques, mass radium or mesothorium on the skin of the abdomen (35, 36). However, both for pelvic lymph nodes and deep seated ENT tumors a greater depth dose was needed. To improve the depth dose it was gradually understood that one had to increase the SSD (for radium) or the FSD (for x-rays) (37). Then, in order to compensate for the dropping dose rate when the radium was moved away from the body surface, one had to use a gram or more of radium. Thus was born mass radium, the radium surface pack, and then teleradium, the predecessor of telecobalt.

Table 3 lists some of the major teleradium units developed between 1913 and 1953 in the effort of find a practical alternative to kilovoltage x-ray tubes (9, 18, 38–40). The telegamma machines were megavoltage (one MV). Thus, they gave a greater depth dose, though at a lower dose rate, while eliminating skin irritation. They had greater flexibility and maneuverability than the early 140 to 200 kilovoltage tubes, and one did not need an engineering degree to operate them. And while there was leakage around the radium container, that was felt to be less of a risk than electrocution. However, these early efforts at telegamma therapy all lacked methods of channeling the rays to the tumor target alone, while sparing the caregivers.

Pioneering work with radium packs and telecurie therapy was done during World War I in the United States, which was unhampered by the European conflict and which had its own refineries since 1913. The beneficiaries of the National Radium Institute; Drs. Kelly and Burnam in Baltimore and the Memorial Hospital in New York, NY, had about 4 g apiece with which to work. The term 'radium pack,' probably coined by H.H. Janeway (1873–1921), came to be defined as a single package (or mass) of radium salts (or equivalent radon gas) totaling 1–4 g. Telecurie therapy was thus initiated in Baltimore and at Memorial during 1913–1920 by utilizing small, portable, handmade, and unshielded packs at distances of 2 cm or more from the skin (4, 41–47).

During 1913–1915, Kelly and Burnam used a radium pack, of at least one gram, at various skin distances up to 10 cm SSD for the treatment of uterine cancer as well as for rectal, abdominal, mediastinal, breast, and brain tumors. They then switched their 5–6 g radium supply exclusively over to radon production. From 1918 to 1922 they worked on a fixed, ceiling mounted, telecurie apparatus which used one to four curies of radon, and which became operational by 1923 (42, 44–46).

At Memorial Hospital in NY, Janeway (1873–1921) took charge in 1912 of Cancer Surgery and Radiation Therapy. He was joined by physicists G. Failla (1890–1960) in 1915, and Edith Quimby (1891–1982) in 1919. In 1917 Janeway, Barrington, and Failla published their two-year experiences with radium and radon using various applicators as well as radium packs at 2 to 5 cm SSD (43). Janeway and Kelly were probably the first to champion the use of the pack at an increasing source-to-skin distance to improve the depth dose. Janeway illustrated this in his report in 1917.

Because of the increasing demand for gamma ray therapy in circumstances of a limited supply, Memorial, like the Baltimore group, switched from radium to radon packs after two years of trials. Failla, in 1928 developed a 4 g pack for Memorial (47), and in 1952, a 50 g unit for Dr. Douglas Quick (1891–1966) at the Janeway Clinic in Roosevelt Hospital, New York, NY (48).

In 1919 at the conclusion of World War I, the UK physicist Sidney Russ was able to procure 2.5 g of war surplus radium bromide from the Munitions Ministry, which had used it for luminous paint. This single radium mass in 18 glass tubes was incorporated into the Middlesex, London, Hospital 'Bomb', which used brass and lead boxes to attempt a single exit portal (24). However, a sharply defined beam was unobtainable (49). After 18 months of use the radium was redistributed into smaller packs. Thereafter, telecurie therapy in the UK lagged until 1929 (4, 12, 13, 24, 50).

In 1921 in Stockholm at the Radiumhemmet, Dr. Elis G.E. Berven (1885–1966), introduced teleradium therapy using a lead protected bomb. In 1923 Dr. Erik Lysholm (1892–1947) published his design of a shielded 'Apparatus

for the production of a narrow beam of rays in treatment by radium at a distance (51). The lead blocked 75% of the gamma rays produced, except for those channeled through the narrow treatment portal. Constantly improved designs were made at the Radiumhemmet while the radium mass was increased from 2 g in 1922 (51), 3 g in 1929 (52), to 5 g in 1937 (53, 54).

In addition to Berven and Lysholm, physicians J.W. Berg (1851–1931), G. Forssell (1876–1950) (9), and J.E. Heyman (1882–1956) worked with physicists Rolf Sievert (1896–1906) (55), Sven Benner (56), and R. Thoroeus (57) at the Radiumhemmet. It developed as an outstanding center for research and for radium, telecurie, and roentgen therapy (4, 58–61). Their teleradium devices were fixed but flexible, shielded (mostly), had a narrow beam to cover a small 5 cm diameter field, and were extremely well suited for head and neck tumors (49).

A different approach was taken at the Radium Institute in Paris. There a 4 g unit was constructed with a wide opening for fields of 150 cm^2 in order to capitalize on backscatter to increase the depth dose (9, 49, 62). Failla at Memorial also built a 4 g unit with a generous field size of 100 cm^2. By way of a wheel arrangement in the head, the radium was well shielded when not in use (47). This arrangement also proved useful in telecobalt designs.

After 1931 physicists in the United Kingdom (Grimmett et al.) and at Radiumhemmet (Sievert et al.) concentrated on small head and neck units with field sizes under 10 × 10 cm (49, 50). Shielding was accomplished in both countries by transferring the source back and forth to a lead safe, 3 m away. The transfer could be accomplished (most of the time) by hand, by a motor-driven wire ribbon, or pneumatically, using a commercial vacuum cleaner (54). Physicists Grimmett and Sievert seem to have, good-naturedly, borrowed heavily from each other (56).

Leonard G. Grimmett (1903–1951) was a graduate of Kings College, London, with a D.Sc. in radiophysics in 1930. From 1930 to 1933 he served as Assistant Physicist at the Westminster Hospital, London, working on radium teletherapy with physicist H.T. Flint, and surgeons E. Rock Carling and Stanford Cade (63). In 1933–1934 he spent a year at the Radiumhemmet. From 1934 to 1944 he was involved in the design and construction of teleradium machines in the UK (64, 65). In 1935 he described the physical properties of a new tungsten alloy (Hevimet) made by General Electric for teleradium shielding (66). In 1936 he designed a 5-g unit with pneumatic transfer of the source back and forth between the treatment head and a lead safe. For this he used an Electrolux vacuum cleaner. He graciously acknowledged his indebtedness to Dr. Sievert of the Radiumhemmet for his original design (67). While employed in Houston, Texas, in 1950 Dr. Grimmett published the first telecobalt design, which employed a wheel to rotate the source and utilized Hevimet but not the Electrolux (68).

After World War II the United States essentially lost interest in teleradium except for the unit at Roosevelt Hospital. This, and a twin unit in Louvain, Belgium, both utilized 50 g of radium (on loan from Radium Belge). The dose rate was only 3 r/min at 10 cm (48). In the UK, however, teleradium units were used, with sources increasing to 10 and 12 g, until the mid 1950s when 100 to 150 curie cobalt-60 sources were substituted (37, 49, 50, 69, 70).

Why were these units so popular in the few places that could afford them? Clinician after clinician swore that the gamma rays were of superior quality. In the 1930s two conferences, in particular, extolled the virtues of telegamma therapy. In 1932 the physics department from Memorial Hospital, N.Y., NY, presented a symposium on the relative effects produced by 200 KV and 700 KV roentgen rays, and by gamma rays (71). In 1935 a symposium on radium packs (telecurie therapy) was held (72). At these meetings and elsewhere clinicians reported a preference for the penetrating gamma rays of radium, although they were hindered by the exceedingly low outputs of teleradium units and their high cost (10, 11, 18, 39, 40, 42, 45, 48, 62, 73–76).

Other perceived teleradium advantages were: a constant rate of dose compared to the variable output of the early x-ray machines and the consequent problems in calibrating them (18, 77), easier manipulation of the unit (62), the absence of ozone and nitrogen oxide (40), and the absence of high voltage electrical current, shocks, and electrocution (40). The teleradium disadvantages were: poor shielding and increased exposure for the care givers, a high cost compared to an x-ray therapy machine—solved by emerging cost of betatrons and linacs, and a low dose rate—solved in 1951 by cobalt-60. Therefore, just as teleradium therapy was about to fade out in 1947, the nuclear reactor would bring new life to the continuing competition between telegamma and x-ray therapy.

Particle accelerators

The 50-year period between Roentgen's discovery 8 November 1895 and the detonation of the first nuclear (atomic) bomb in the New Mexico desert in July 1945 represents the initial development of nuclear physics, radiochemistry, and atomic manipulation. This basic research would quickly lead to commercial, medical, and military applications. The world of medicine and the training of physicians would change drastically. New medical knowledge in microbiology and pharmacology was joined by the startling advances in atomic physics which brought the 'machine age' to medical practice. A physiologist, Marshall Brucer, who ended up in nuclear medicine expressed the feelings of many physicians when he claimed that 'science died about 1900 and engineering took its place' (78).

Between 1901 and 1951 the Nobel prizes for physiology/medicine were awarded for discoveries in infectious disease (diphtheria, malaria, tuberculosis, syphilis, typhus, yellow fever), penicillin, immunity, insulin, the EKG, vitamins, and ACTH among others. The medical science of radiology, however, developed as a result of the discoveries and research studies in physics and chemistry. These Nobel winners, who are most significant for radiologists, include the following: Roentgen, Becquerel, the Curies, Lenard, Thompson, Rutherford, von Laue, the Braggs, Barkla, Plank, Einstein, Soddy, Bohr, Aston, Millikan, Compton, Wilson, de Broglie, Urey, Chadwick, Joliot, Joliot-Curie, Fermi, Lawrence, von Hevesy, Hahn, Cockcroft, Walton, McMillan, and Seaborg. Hereafter Nobel Prize winners are marked in this narrative with an (*).

The Joliot-Curies* in 1934 had suggested that the artificial (man-made) radioisotopes which they had created could also be synthesized by using deuterons as projectiles in place of the polonium alpha rays which they had used (79–81). This, of course, required a particle accelerator machine of sufficiently high voltage to penetrate the nucleus. This accelerator had been sought since 1919 when Rutherford* began using alpha particles for nuclear transformation (8). In 1932 that goal became a lot closer with the discovery of the neutron, the discovery of heavy water (deuterium), and the invention of the Cockcroft* and Walton* particle accelerating 'atom smasher' (82). However, the laboratory that then proceeded to capitalize on induced artificial radioactivity by machine accelerated particles was the University of California, Berkeley Radiation Labaoratory under the direction of E.O. Lawrence* (1901–1958). The Lawrence Berkeley Laboratory would go on to develop the modern linear accelerator, electron and proton synchrotons, and heavy ion accelerators. By following up on the work of the Joliot-Curies* and Fermi*, the Laboratory established itself as a prolific producer of new radioactive substances, including cobalt-60 in 1937, and it discovered the true transuramic elements No. 93 (Np) and No. 94 (Pu), for which E. Fermi* had mistakenly been awarded the 1938 Nobel Prize (82–87).

In 1928, the year that Lawrence was starting work in Berkeley, there was a growing interest among physicists in the use of high voltage transformers for nuclear physics accelerators as well as in high voltage x-ray tubes for cancer therapy. Physicists: C.C. Lauritsen (1892–1968) at the California Institute of Technology (Cal. Tech.), D. Sloan at the University of California, Berkeley, and G.S. Innes in London developed transformer and tube combinations for 'supervoltage' cancer therapy. Supervoltage came to be defined as over 500 KV (88). R.J. Van de Graaff (1901–1967) at the Massachusetts Institute of Technology (MIT) invented an electrostatic generator with megavoltage potential. Tubes in Detroit and London were powered by Cockcroft-Walton generators. From 1930 to 1939 the race was on for supervoltage and megavoltage cancer therapy machines, and the nuclear physics laboratories were working with commercial concerns like General Electric (G.E.), Kelley-Koett, and Metropolitan Vickers for science, for humanity, and for profilt (10, 89–93). Table 4 demonstrates the chronology of development of x-ray therapy machines from 1896 to 1956.

W.D. Coolidge (1873–1975) became acquainted with x-rays in 1896 during his senior year at Boston Tech, the future Massachusetts Institute of Technology (MIT). In 1910 he developed a tungsten filament for light bulbs, which was to be the basis for his revolutionary new 'hot cathode' x-ray tube of 1913. This tube utilized tungsten, which had previously been unworkable, for both cathode and anode, and made positive ions (gas) unnecessary. It was based on research developments in the electric light industry. By 1922 he had developed the 200 KV 'deep therapy' tube for G.E. (4, 8–10).

This first 'deep therapy' unit was installed for use by pioneer radiologist Dr. James T. Case (1882–1960) at the famous Battle Creek, Michigan, Sanitarium—a combination modern medical center, vegetarian-nutrition clinic, and hydrotherapy, exercise, vacation, and health spa (9, 19, 73, 94, 95). The institution was owned and operated by the local Seventh Day Adventists who coined 'sanitarium' to distinguish it from institutions for mental and tuberculous patients (a sanatorium) (96). The Adventists were a century ahead of their time in opposing the nineteenth century zeal for overmedication, for overeating, and for abusing tobacco and alcohol. The Sanitarium Superintendent was John Harvey Kellogg (1852–1943), and the business manager was Will Keith Kellogg (1860–1951) (4, 92, 94).

The Kellogg brothers, between 1895 and 1905, experimented with 'health foods' and developed granola, peanut butter, cereal coffee (later Postum), toasted wheat flakes, and toasted corn flakes. Others, including C.W. Post (a former patient) went on to market these Sanitarium items for their own financial gain. Finally in 1906 W.K. Kellogg quit the Sanitarium and went into the toasted corn flake business for himself. Dr. Kellogg demurred for fear the business would be 'unprofessional.' The Sanitarium entered bankruptcy in 1938 and was sold to the military in 1942. W.K. Kellogg, however, prospered and left $47 million to charity between 1930 and his death in 1951 (94). In addition he would personally fund one of the original 'supervoltage' therapy units in 1931.

During 1926–1928 Coolidge, stimulated by competition from Germany, worked on higher voltage 'cascade tubes' (10, 19, 90). During this time Coolidge announced a new tube, 11 feet long, which he hoped would 'produce x-rays as penetrating as radium gammas and/or produce electrons in the same quantity as from a ton of radium'. This 'cascade tube' produced high energy electrons (900 KV),

Table 4

X-ray therapy machines (1896–1956)

1896	Cathode ray tubes; 70 KV (50–100), Crookes, Hittorf, Lenard, etc.
1913	GE-Coolidge, 140 KV, 'hot cathode' tube
1922	GE-Coolidge, 200 KV, 'deep therapy' tube
1930	GE-Coolidge, 350 KV, 'cascade' tube, 11 ft. long
1930	(1) C.C. Lauritsen tubes from Cal. Tech, 30 ft long using GE transformers in series. (a) 600 KV tube at the High Tension Lab. Used by Dr. A. Soiland from Los Angeles from Oct. 1930–Sept. 1932 (b) 600 KV tube for Dr. Soiland for the Los Angeles Tumor Institute (c) 750 KV tube for the Kellogg Lab at Cal. Tech. Used by Dr. S.G. Mudd Sept. 1932–1937 (2) Lauritsen tubes made/sold commercially by Kelley-Koett (d) 1931: 600 KV for Harper Hospital in Detroit (e) 1933: 650 KV for Lincoln General, Nebraska (f) 1936: 600 KV for Miller Hosp., St. Paul, Minn.
1931	GE-Coolidge, 750 KV 'cascade tubes.' (a) Oct. 1931; Memorial, NY, NY, 600–750 KV (b) Oct. 1933; Chicago Mercy-Loyola Univ. 600–800 KV; tube (c) Jan. 1934; Swedish Hosp., Seattle 600+ KV
1932	David Sloan and J.J. Livingood, graduate students of E.O. Lawrence at the Berkely Radiation Lab modify a radiowave resonant transformer proton accelerator to produce 700–750 KV x-rays in a self contained tank housing both tube and transformer. University faculty and staff with $6–12 000 of Crocker money installed two units. (a) 1933: University of California, San Francisco Hospital (b) 1933: Columbia Presbyterian, NY City
1934	R.J.V. de Graaff develops electrostatic generator, at MIT, with 7 MV potential but has no capatible tube. 1936: Tube and generator installed at Boston hospital 1937: First patient treated at true 1 MV, March 1
1934	St. Bartholomews Hospital, London, contracts with Metropolitan Vickers for a high voltage therapy unit powered by Cockcroft-Walton cascaded generators 1937–39: Unit operates at 700 KV 1939: Operates at 1 MV
1935	GE markets 400 KV models from stock
1939	GE Maxitron, 1 MV Freon-insulated, resonant frequency transformer, in tank 7.5 × 4 ft
1940	1.25 MV; Van de Graaff
1942–3	2 MV; Van de Graaff and GE
1948	Tubeless betatron, 20–22 MV; in Urbana, IL, first patient treated April
1949	Saskatoon, Saskatchewan; betatron regular clinical use starts, March
1953	Hammersmith Hospital, London, first patient treated by medical linear accelerator (8 MV), August

but it would be another three years before x-rays could be produced (10). The 'Coolidge tubes' became a big business for G.E. Following World War I, they bought an x-ray equipment manufacturing company in Chicago, Victor Electric, to make their tubes. In 1930, Victor X-Ray Corp. became G.E. X-Ray Corp.

In 1926, Charles C. Lauritsen (1892–1968), a Danish-American engineer was working for a radio manufacturer in St. Louis when he heard Robert Millikan* (1858–1953), the C.E.O. at Cal. Tech., lecture. Lauristen thereupon moved his family to California, and began work on a Ph.D. in physics under Millikan. Southern Calif. Edison had established a high tension (voltage) laboratory (H.T.L.) there in order to study long distance electric power transmission. At HLT Lauritsen used a cascade of 250 KV transformers to produce, at the peak of the alternating current cycle, 750 KV x-rays in a 30 foot long tube housed in a tower 14 feet high and 8 feet square across the base. In 1930 Luaritsen applied for a patent for a one MV x-ray tube for cancer therapy. In the application he stated: 'I have

found that when (one MV) potentials are employed, radiations, substantially the frequency of the gamma radiation from radium, may be obtained from the tube embodying my invention' (97).

Dr. Albert Soiland, born in Norway, was a 1900 graduate of the University of Southern California School of Medicine and one of the founders of the American College of Radiology in 1923 (9). In the summer of 1930 Lauritsen and Millikan* invited Dr. Soiland (1873–1946) from the Los Angeles Tumor Institute (LATI) to inspect the 750 KV tube. Thereupon, Dr. Soiland began to bring his patients, at night, to the HTL for treatment from October, 1930, until September, 1932 (97). The giant tube was found to function most reliably at a constant potential of 600 KV. This patient group was reported on at the RSNA in December, 1932 (88). Dr. Soiland had a 600 KV tube made for his own use at the LATI (9, 98, 99).

Meanwhile physicist Millikan* sought funds in 1931 for a new laboratory at Cal. Tech. to study particle acceleration. He found two benefactors, which then allowed him to switch the cancer therapy (always a potent fund raiser) to a new laboratory, while using the HTL for nuclear physics research.

The Mudd family philanthropic trust (copper & sulfur mines) contributed with operating funds for 5 years and Dr. S.G. Mudd, who agreed to serve without salary as the attending radiologist. Contributing the money, in March of 1931, for the building, equipment, and maintenance of the Kellogg Laboratory was W.K. Kellogg (94, 97). The first patients (four could be treated at one time) were treated at Kellogg in September, 1932, using a cascade of transformers from G.E. and the 30 foot long Lauritsen tube, operating at 600 to 750 KV and on occasion at 1 000 KV. The apparatus cost $50 000 and delivered 20 r/min at 70 cm FSD (92). Initial impressions were reported in September, 1933, at the American College of Radiology and results 'compared favorably with treatment by 4 grams of radium' (100).

From 1932 to 1937, the Kellogg Laboratory and its budget were devoted largely to radiation therapy (101) but also to nuclear physics. The latter took place in the adjacent HTL, where the x-ray tube was modified to accelerate ions, producing neutrons and artificial radio-isotopes. In August, 1932, Cal. Tech.'s C.D. Anderson* earned a Nobel prize by discovering the positive electron. By 1939 Mudd and Kellogg withdrew their support and in 1940–1941 the laboratory became a major design and production center for rockets (97). Lauritsen headed a rocket-project staff of more than 3 000 and became the proverbial 'rocket scientist' to which the common man endures relentless comparison.

The Kelley-Koett Co. outfitted and sold, at $29 000 each, at least three other Lauritsen 30-foot tubes to Harper Hospital in Detroit in 1931, Lincoln General in Nebraska in 1933, and to Miller Hospital in St. Paul in 1936 (4, 92, 93, 102). The one in Detroit was powered by an array of Cockcroft-Walton generators (103).

E.O. Lawrence had come to Berkeley in 1928, interested in the use of high-voltage machinery for nuclear physics research. By 1930 he had begun work on linear accelerators, as well as on the cyclotron. One of Lawrence's many projects was with graduate student David Sloan, who was an electronic specialist hired away from G.E. in Schenectady, where he worked on x-rays and vacuum tubes. In the fall of 1931 Lawrence directed Sloan to a resonant frequency (radio-wave) transformer as an alternative to the cyclotron for producing fast protons. During 1932 Sloan and J.J. Livingood succeeded in producing x-rays of 700 KV. Two machines based on this work were installed in hospitals; from December of 1932 to June of 1933 at the University of California Medical School in San Francisco, supervised by radiologist Dr. Robert Stone (1895–1966), and from June through December of 1933 at Columbia University Presbyterian Medical Center, F.C. Wood Institute of Cancer Research (9), supervised by physicist F.M. Exner. Developmental funds, $6 000 to $12 000 per machine, were solicited from the Crocker brothers; William H. (west coast) and Charles (east coast) (87). The philanthropic brothers were heirs to the fortune of one of the Central Pacific's 'railroad barons' (Crocker, Hopkins, Huntington, Stanford), (104).

The Sloan tubes delivered a beam of approximately 700–800 KV. The entire unit was contained in a vacuum tank, measuring 40 inches high and 42 inches in diameter, which both contained the transformer and served as the x-ray tube! General Electric would later (1939) develop a resonant transformer with the same arrangement (105). A major safety factor was the elimination of any high voltage outside the tank (106). Mrs. Gunda Lawrence, the mother of Ernest and John, was diagnosed in November, 1937, at the Mayo Clinic as having an inoperable, incurable uterine tumor. She was irradiated with the high energy Sloan tube in Dr. Stone's department at U.C. San Francisco and made a miraculous recovery, which cast suspicion on the diagnosis (87).

Robert Jemison Van de Graaff (1901–1967) had started work at the Alabama Power and Light Company after obtaining his engineering degree from Alabama. He then went to Oxford on a Rhodes Scholarship for a Ph.D. in physics in 1928. Working at Princeton from 1928–1931 he developed an electrostatic generator device with a potential of 1.5 MV at a cost of $100. In 1932 Karl Compton hired him at MIT. Further work on his huge but cheap generator was then done in an abandoned Zeppelin hangar, where he moved the unit via 14-foot-wide railroad tracks (87). By 1934 he had obtained a 7 MV voltage potential, but he lacked a compatible tube. However, on 1 March 1937, a one MV tube and generator unit was available for treatment at the Collis P. Huntington Memorial Hospital in Boston (107, 108). The first patient to receive treatment

with this true one MV (constant potential) x-ray beam was a dentist with bladder cancer who was reported to have outlived the hospital, which closed in 1941 (92).

This unit cost about $26 000 and had an output of 40 r/min at 80 cm. In 1939 the unit was downsized and upgraded to 1.2 MV with an output of 80 r/min at 100 cm when installed at the Massachusetts General Hospital. By 1940, two MV was available. After the War commercial production and marketing by the High Voltage Engineering Corporation at MIT resulted in the sale of 43 of the two MV Van de Graffs by the end of their production in 1969 (92).

J.D. Cockcroft (1897–1967) and E.T.S. Walton (b. 1903) had achieved nuclear penetration in Rutherford's* Cavendish Laboratory at Cambridge in 1932 with a 710 KV proton beam, the first 'atom smasher' (82). St. Bartholomew's Hospital, London, commissioned Metropolitan Vickers in 1934 to make a megavoltage x-ray therapy unit based on their potential voltage multiplier. From 1937 to 1939 it operated at 700 KV, and from 1939 to 1960 at one MV for physicist G.S. Innes (109, 110).

Coolidge at G.E. perfected his high voltage 'cascade tube' for installation at Memorial Hospital in NY in 1931 (111). Rated at 750 KV, other unique and custom made units were sold to Mercy Hospital in Chicago in 1933 (cost $65 000) and to Swedish Hospital in Seattle in 1934 (89, 93). Unfortunately, these units required a large building because they were large (and unwieldy) and they required significant ground clearance because they were air insulated. And at high humidity they operated poorly (93). However, by 1935 G.E. was able to market stock models with 400 KV energy potential (112).

By 1939, General Electric had made significant advancements and improvements in the 'supervoltage' (over 500 KV) units, such as miniaturization and use of the new refrigerant Freon as an insulating gas in place of either air or oil. A one MV resonant frequency transformer unit was enclosed in a shock-proof Freon-filled tank measuring only 7.5 by 4 feet (113). During World War II tank size was reduced further, the tube was sealed off so that a vacuum pump was no longer necessary, and the Freon was replaced by sulfur-hexafluoride. These units were then used for x-raying aircraft engines and heavy steel armaments. In 1946 two MV units were available. By the end of production in 1963, G.E. had sold about 16 two MV and 15 one MV units (92, 93). Thus true megavoltage, at a constant potential of one-two MV, x-ray therapy machines were achieved first by Van de Graaff in March, 1937, and then by Metropolitan Vickers and General Electric in 1939.

After the War the University of Illinois in Chicago (114), and H. Johns (physicist) and T.A. Watson, M.D., in Saskatoon pioneered the use of the nuclear physics betatron (115, 116) to treat patients with 20–22 MV x-rays in 1949–1951. John's group started regular patient treatments in March, 1949 (4, 117, 118). By 1955 a dozen betatrons were in clinical use; by 1968, 27; by 1973, over 50 in the USA and Canada (92, 93).

Table 5

1986 survey by the American College of Radiology of teletherapy units

Location	No. of Van de Graaffs	No. of Beta-trons	No. of Cobalt 60s	No. of Linacs
USA	18	45	700	1 200
Elsewhere	6	175	1 700	1 000
Worldwide Total	24	220	2 400	2 200

Following through on their wartime research in microwave technology for radar, workers in the UK and at Stanford, California, developed the medical linear accelerator for x-ray therapy. The first medical unit was installed at Hammersmith Hospital, London, in 1952; and therapy commenced in August, 1953. By 1955 the UK had three 4 MV units and one 8.5 MV linac in use. Stanford started patient treatments in January, 1956 (92, 93, 119, 120).

In the thirty years from 1939 to 1969, the approximate total sales of megavoltage x-ray units were reported to be no greater than 136: Van de Graffs, n = 43; linacs, n = 35; General Electrics, n = 31; and betatrons, n = 27 (92). By contrast, during the first 10 years of telecobalt production, 1951–1961, 1 120 units were sold, 422 of them in North America (121). After 1969, with the introduction of the 4 MV model, linacs became more reliable, more affordable, and increasingly popular. Interestingly, however, a 1986 worldwide survey (122) revealed that telecobalt therapy has continued to maintain a significant presence, especially in areas where cost is a factor, Table 5.

Synthetic radium

As Lawrence* worked on improving his cyclotron particle accelerator, three new discoveries made its development even more relevant to nuclear physics (87). In December, 1931, heavy hydrogen (D2) (the deuteron) was discovered. In February, 1932, the neutron, and in April, 1932, nuclear disintegration by accelerated proton ions were announced by Rutherford's associates at Cambridge (8, 82). Then in January, 1934, the Joliot-Curies* announted their New Year's Eve experiment which produced synthetic (artificial) radio-isotopes, along with their suggestion that deuterons, which required an accelerator, would work better than their polonium alpha particles (79–81). The Berkeley Lawrence Laboratory was off and running now with a prime 'raison d'être.' By April of 1934, E. Lawrence* said, 'We are not unmindful of the possibility that we may find a substance in which the radio-activity may last for days instead of minutes or hours, in other words, a substance from which we could manufacture synthetic radium' (87).

While the cyclotroneers at Berkeley were first producing radioisotopes with machine-accelerated particles in 1934–1935, Enrico Fermi* (1901–1954) was doing it the old-fashioned way in Rome. With radon as a source, alpha particles were targeted against beryllium to produce projectile uncharged neutrons. Fermi superseded the Joliot-Curie's work by producing scores of new isotopes (8, 24, 82). In bombarding cobalt, in 1934–1935, with these neutrons, he produced a gamma emission which indicated nuclear (isotope) transformation and decay after neutron capture by the nucleus. In 1936 workers at Princeton suggested that neutron capture by a stable cobalt-59 isotope could yield a cobalt-60 nucleus with strong activity and a half life of over one year (123). J.J. Livingood and G.T. Seaborg at Berkeley then published three papers on radioactive cobalt: 1937, 1938, and 1941 (124–126). By 1941 cobalt-60 isomers with activities of 10.7 min and 5.3 years had been separately identified by them. At the end of World War II, in November 1945, when scientific censorship was finally lifted, the megavoltage gamma ray energy (1.1 to 1.3 MV) of the 5 year isomer was published by the MIT cyclotron workers (127). The authors' only practical suggestion for cobalt-60 was for its use as a laboratory gamma ray standard, due to its long half-life and homogeneous radiation.

With the close of the War in August, 1945, nuclear piles (reactors) were revealed to be a much more efficient source than cyclotrons for megacuries of radioisotopes. Indeed, as part of wartime secrecy, the American reactors shipped isotopes to cyclotron departments for them to distribute. The existence and awesome capabilities of the reactors were thus kept secret while researchers were kept well supplied (24). At the end of the War the Americans had several reactors functioning while Canada had only one, and the rest of the world had none (128). However, the Canadian reactor at Chalk River, Ontario, had two big advantages: it used heavy water instead of carbon (graphite) as a hydrogen moderator, and it had some very talented emigrant physicists working there.

Castoffs in Canada

The very existence of a Canadian reactor was a quirk of fate. Before World War II started in 1939, the three leading nuclear physics research centers were: Rutherford's* group at Cambridge, the Joliot-Curies* in Paris, and the Otto Hahn*-Lise Meitner-F. Strassman group at the Kaiser Wilhelm Institute in Berlin (129). Shortly after the discovery of nuclear fragmentation in December, 1938, by the radiochemist Hahn*, Jewish physicists Meitner and her nephew Otto R. Frisch, in exile in Scandinavia, were notified. They confirmed the discovery and coined 'fission' in January and February of 1939 (82, 129, 130).

The Joliot group then published a prediction that a large release of energy by a fission chain reaction might be possible with a solution of uranium in ordinary (or better yet, heavy) water as a source for hydrogen moderators (8, 131–134). Joliot's Jewish colleagues H.H. von Halban (Austrian) and Lew Kowarski (Slavic) secured 185 kg of D_2O, in 26 cans, from the Norsk Hydro-Elektrisk Kvaelstofaktiesellskap (hydroelectric plant) in Norway which produced it (D_2O) as a byproduct from making ammonia fertilizer (135). Sneaking it back to France in March, 1940, during the 'phony war' winter lull of 1939–1940, they had barely begun their experiments on fission-chain reactions when France fell in June, 1940. They escaped with the D_2O to Cambridge to continue their research as guests of the UK. Joliot (1900–1958) stayed to look after his family (Irene suffered from tuberculosis), protect his cyclotron, and to be active in the Resistance. He had also sought patents on the fission process and had continued publishing his results after the War started, and thus was never popular with the Manhattan Project (8, 130).

As soon as Adolf Hitler had become Chancellor of Germany in January, 1933, Jewish physicists, led by Albert Einstein* in 1932, started leaving German-dominated Europe. Eventually even non-Jewish scientists like E. Fermi* in 1938 and N. Bohr* in 1943 were forced to flee because of Jewish relatives (8, 82). This made the United Kingdom and the United States the beneficiaries of a talented scientific influx. However, the Manhattan Project, which after June, 1942, was run by the US Army, was always suspicious that these anti-Fascist immigrants were either Communist spies or being blackmailed because of relatives in Nazi death camps. The US tried to do thorough security checks on any scientist involved in nuclear research and was highly skeptical of the lax investigations that the beleaguered war-torn UK conducted on their welcomed immigrants (5, 130, 135–137).

In March of 1940 two such émigré physicists in the UK, Otto R. Frisch and Rudolf Peierls, suggested that an atomic bomb was feasible (135). An interchange of strategic scientific information between America and the UK started with radar in April, 1940, when H. Tizard and J. Cockcroft visited here. By October, 1941, the British MAUD report had convinced the Americans to finance and begin work toward an atomic bomb (135). W.D. Coolidge and C.C. Lauritsen (now a rocket scientist) were, among others, involved in the discussions leading to this decision (135).

The American bomb effort began in earnest during June to September of 1942, when Gen. Groves and the US Army took over the Manhattan Project. In August, 1943, the Quebec Agreement brought 28 UK scientists into various components of the Manhattan Project, including Los Alamos. British refugee scientists who had not become UK citizens were excluded as security risks. The British then suggested a joint British-émigré-Canadian laboratory be established in Montreal for nuclear research to lead to construction of a pilot reactor, moderated by D_2O, for

plutonium production. With H.H. von Halban (1908–1964) as director, this group started work in Montreal in late 1942, but received no American cooperation until April, 1944, when émigré von Halban was replaced as director by English J.D. Cockcroft*. The Americans now agreed to furnish the Montreal group with the secret information and the necessary materials to build their own reactor. Cockcroft* brought heavy water expert, engineer and physicist Lew Kowarski (1907–1979) over from Cambridge to Canada to design their reactor. Kowarski had stayed in the UK because he was incompatible with his French colleague von Halban except in the presence of F. Joliot*. The Argonne Laboratory in Chicago had brought into operation a heavy water low-energy reactor (cP 3) on 15 May 1944. Kowarski was allowed a visa to study this. In August of 1944 remote Chalk River, Ontario, was chosen as the site for the first Canadian experimental reactor (ZEEP), which went critical 5 September 1945 (4, 5, 130, 134, 137).

The British-paid scientific staff employed at the Montreal Laboratory numbered 88 and included U.K. citizens J.S. Mitchell, J.V. Dunworth, H.F. Freundlich, J.D. Cockcroft, and A.N. May as well as émigrés P. Auger, J. Gueron, H. von Halban, L. Kowarski, B. Pontecorvo, and B. Goldschmidt (137, 141, 144). After August, 1945, many of the staff, including von Halban and Kowarski, went 'back home' to build reactors in France and England. Alan Nunn May and Bruno Pontecorvo were found to be Soviet spies, aiding the rapid development of a Russian reactor. Also aiding the Soviets was German emigrant and U.K. citizen Klaus Fuchs, the son of a Lutheran minister, who served at Los Alamos and later became one of the directors of the British reactor at Harwell. In 1950 he was discovered to have been a Soviet spy since 1942, and like May and Pontecorvo a dedicated Communist since his undergraduate days (138, 139).

Also on the British staff at Canada in 1944–45 was a physician-physicist, Joseph Stanley Mitchell (140, 141). Born in 1909, Mitchell received his Bachelor of Medicine at Birmingham in 1934. After service as a house physician, he became a Fellow at Cambridge, St. John's College, obtaining his Ph.D. in 1937. He did radiology and therapy training from 1937–9 in Manchester at the Christie Hospital for Incurables-Holt Radium Institute complex under Dr. Ralston Paterson (9). He returned to Cambridge in 1939 as a radiotherapist. From 1946–57 he was Head of the Radiotherapy Department at Cambridge, and in 1957, became Regius Professor of Physics there.

During 1944–1945 Dr. Mitchell served as the Chief of Medical Investigations for the Montreal Laboratory, NRC (National Research Council of Canada) (140, 141). In 1946 Mitchell published articles (142, 143) where he recommended 1.2 MV cobalt-60 gamma rays as a teleradium substitute, and the Canadian reactor as the vehicle for practical production. He acknowledged J.V. Dunworth as co-author for these ideas, as first suggested in an uncirculated official wartime reports in Canada dated 26 March 1945 and entitled: 'Application of Nuclear Physics to Medicine and Biology' (5). Also involved with this concept were the eminent British radiation physicist Wm. Valentine Mayneord (1902–1988) and the Canadian A.J. Cipriani, who was Chairman of the Biological and Medical Research Branch of the Atomic Energy Project at Chalk River. They co-authored a 1947 study on 'The Absorption of Gamma-Rays from Cobalt-60' (144). Mayneord spent 1945–1946 as an advisor to Cipriani at Chalk River while on leave from the Royal Center Hospital in London, where he was the Director of the Physics Department at the Institute of Cancer Research (9). He had a long and distinguished career in radiation-medical physics, and is credited with a major role in the invention of the 'rad' during 1937–1954. His stature in radiation physics was such that the current SI unit for 1 joule/kg might just as appropriately have been called the 'Mayneord' instead of the 'Gray' (24).

Harold Johns

Physicist Harold Elford Johns (b. 1915) first met Professor Mayneord in Augst, 1946. This encounter was to significantly influence Johns (145, 146). After a two-week exposure to Britain's leading radiation physicist, Johns went on to write four editions of The Physics of Radiology between 1953 and 1983, which remained a standard for over three decades. He also helped pioneer adoption of the nuclear physics betatron (electron accelerator) for clinical use in 1948–1949, and almost single-handedly designed and developed one of the first two commercially successful telecobalt machines, later to be manufactured by the Piker Co. (1, 4, 117, 118).

Harold Johns was born in West China of Canadian parents. His parents had gone to China in 1910 as missionaries of the Union University Committee of Quakers, Anglicans, and Methodists. They returned to Canada in 1925. After positions in Vancouver and then Brandon, Manitoba, his father taught at McMaster University in Hamilton, Ontario. Harold Johns finished his undergraduate work at McMaster in 1936 and his Ph.D. at Toronto in 1939. He had won the coveted '1851 Exhibition Science Scholorship' to Cambridge, and thus had hoped to follow in the footsteps of Lord Rutherford (1871–1937) (82). However, the events of September, 1939, sent him instead to a war job in Edmonton, Alberta. He was involved in teaching physics, especially RADAR, to pilots and other service personnel. He was also the official radiographer for the magnesium castings which held the airplane engines together (personal interview, Toronto, June, 1990).

At war's end Johns took a job teaching in the Physics Department of the University of Saskatchewan and working with the Saskatchewan Cancer Commission under the direction of Dr. Allan Blair. He thus became Canada's first

medical physicist. During the summer of 1946 he was sent on a tour to the leading radiotherapy centers in the United States. This was followed by attending the two-week lecture course on radiotherapy physics given by Professor Mayneord in Toronto. Johns, being the only physicist present among therapists like Vera Peters, was asked to take notes and provide comprehensive copies for the attendees. This became the basis for his highly readable radiology-physics books. Mayneord also extolled the therapeutic possibilities of such tubeless wonders as the betatron electron accelerator which was currently in use at the University of Illinois as a nuclear physics tool, and cobalt-60 as a radium substitute in telegamma therapy (4, 6, 145–147).

Johns first followed up on the betatron. Developed originally in 1940–1941 as an instrument primarily for physics research, it was believed since 1943 that it could be used for 'deep therapy' using high energy (20 MV $\pm$) photons or electrons produced without the need of a high voltage tube or transformer (115, 116). Finally, in April 1948, the University of Illinois in Urbana gave permission to try the 22 MV photon beam for treatment of a brain tumor in a 22-year-old physics graduate student (148). Dr. Johns visited Urbana to study this therapy attempt. He was able to procure a commercial betatron machine from the Allis Chalmers farm equipment manufacturer in Milwaukee for the Saskatoon Cancer Clinic in the summer of 1948. Patient therapy started in March, 1949, after nine months of testing and obtaining depth doses and isodose curves (117, 118, 145). The physician working with Dr. Johns was Thomas Alastair (Sandy) Watson (1914–1987), a native of New Zealand who had also been a medical missionary in China before studying radiotherapy in Manchester, England, just prior to World War II. Immigrating to Saskatchewan, he became director of cancer services for that province. In 1963 he became Director of the London Clinic of the Ontario Cancer Foundation at Victoria Hospital, upon the death of Dr. Ivan H. Smith, who had also trained at Manchester (9, 149).

Chalk River, Ontario

The first Canadian nuclear pile (reactor) named ZEEP (Zero Energy Experimental Pile) was superseded in July, 1947, by the NRX with its superior neutron flux. It was raised to full power one year later. This second Canadian reactor (NRX) provided a greater neutron flux than any reactor in the USA. The flux was rated at 10 to 20 $\times$ that of a graphite-moderated reactor of comparable power. This was felt to be due to the smaller physical size of NRX, made possible by the use of the more efficient D_2O, and it did not require enriched fuel. Anticipating a commercial market for radioisotopes, the Canadian government turned to the crown (government) corporation that had been processing and selling radium products; the Commercial Products Division (CPD) of Eldorado Mining and Refining Limited. The CPD took over the processing and distribution of the NRX-produced isotopes. Heading up the CPD for the government was Roy Errington, a graduate of the University of Toronto with an M.A. in mathematics and physics. In addition to distribution, the CPD also expanded, under Errington, into the manufacture and sale of accessory equipment. In 1952, CPD would be joined with the Chalk River reactor into a newly created crown (government) corporation called Atomic Energy Canada Ltd. (AECL) (5).

In 1950, Dr. A.J. Cipriani, Head of the Biology Division at Chalk River, got three separate requests for the use of the NRX reactor to prepare 1 000 curie cobalt-60 sources for teletherapy use. One originated with H.E. Johns, Ph.D., and T.A. Watson, M.D., at the University of Saskatchewan. The physicist Johns had worked out a tentative design. The other Canadian request came from R. Errington, M. Sc., and Don T. Green, B. Sc., at Eldorado's Commercial Products Division (CPD) in Ottawa in conjunction with Ivan H. Hamilton Smith, M.D., (1904–1963), London Clinic, Ontario Cancer Foundation (5, 150). The third request came from a United States partnership represented by the Oak Ridge Institute of Nuclear Studies (ORINS); Monroe Dunaway Anderson Hospital in Houston, Texas (MDA), and General Electric (GE) in Milwaukee (24, 65, 147, 151, 152).

Gilbert Fletcher

The American effort originated with Gilbert Hungerford Fletcher, M.D. (1911–1992), at M.D. Anderson. Fletcher was born in France of an American businessman father and a French mother. His paternal grandfather (d. 1887) had been a Civil War veteran and Protestant minister in Springfield, Massachusetts. Gilbert's father Walter (1872–1914), an import-export merchant, died at age 42, leaving a large estate.

Gilbert's mother, Marie Boudol, was one of some 13 children from a farming family in Provence. Marie Fletcher was described as rebellious, fiery, loquacious, opinionated, and fond of discussing politics. In 1929 Gilbert graduated from a prestigious private preparatory school, Stanislas, which counted Generals Foch and de Gaulle as alumni. By then passing the examinations at the University of Paris for the French Licence des Lettres, he obtained the US equivalent of a B.A. After 1929, the family moved to Brussels. Gilbert commuted to and from the University of Louvain, where he obtained another B.A. in civil engineering in 1932. He switched to the University of Brussels for an M.A. in mathematics in 1935, and then completed the course work for a Ph.D. in physics by 1937. Instead of completing the thesis, he switched to the medical school (1937–1941), where in his second year he was advised that his peripatetic ways would lead to certain

failure. In his engineering and physics studies, and then in the third year of medical school, he was exposed to Belgium expertise in radium therapy for cancer. Several grams of radium had been graciously loaned out by the Union Minière to the Brussels medical school, which was only 48 km from the world's biggest refinery at Olen. Fletcher spent a six-month externship in the cancer clinic, where radium and 250 KV were the treatment options. He had found his life's work. By the time of his graduation from the University of Brussels medical school in 1941, he was focused on radiation therapy (especially radium brachytherapy and telegamma therapy) and on emigration.

In 1932, at age 21 he had elected to retain his American citizenship rather than the French. In 1941, with the possibility of incarceration when America eventually entered the War, and with a trust fund in a New York City bank that was not available to him in Nazi-occupied Belgium, Fletcher decided to emigrate. He was refused an exit visa, and so with 250 francs escaped into unoccupied France and then to Lisbon. There a trusting Jewish merchant from Brooklyn loaned him freighter passage. He left Lisbon by Portuguese freighter in November, 1941, and arrived in New York City in January, 1942. After several weeks spent satisfying wartime internship requirements and learning English, Fletcher made inquiries about radiation therapy training at Memorial Hospital, which meant a surgery residency. He credits Edith Quimby with guiding him, instead, into a radiology residency at New York Hospital, 1942–1945. In 1943 he married Mary Walker Critz, a pediatric-ophthalmology resident from Mississippi. In March, 1945, he entered the US Army for duty at the Pittsburgh VA Hospital, fluoroscoping the upper gastrointestinal tract for two years. In 1945, after the atomic bomb explosions of July and August, the wartime secrecy acts were dissolved, and physics journals exploded with radio-isotope data. Thus by 1945–1946 Dr. Fletcher became aware of the possibilities of cobalt-60 and began talking about possible telecobalt machines (personal interview with Gilbert Fletcher, June, 1989) (9, 153, 154).

On October 31, 1947, a Conference on Multimillion Volt Radiations and Their Use in Cancer Research and Therapy was held in Bethesda, Maryland, at the National Institute of Health (NIH) (155). Thirty-three consultants comprised this National Advisory Cancer Council. Six members were from the National Cancer Institute (including H. Kaplan), 5 from the NIH, 2 from the National Research Council, and 16 from outside the government (including S.T. Cantril, G. Failla, D. Kerst, R. Stone, M. Tuve). The physicians and physicists at this meeting were among the most outstanding leaders in American radiation therapy in 1947. These consultants were asked for advice about requests for government funding in building and operating high-voltage equipment. Five types of equipment were discussed: 1) electrostatic generators (up to 2 million volts), 2) betatrons, 3) proton beam from a synchrocyclotron, 4) a synchroton, and 5) a linear accelerator beta ray beam (155).

Pertinent comments reflecting the general tenor of the meeting included the following: 'More can be done to improve the cancer situation within the next five years (1947–1952) by producing more and better trained radiation therapists than can be accomplished merely by increasing the voltage of the radiations to the multimillion range.' The government should consider support of at least three betatrons of 35–50 million volt range, 2 to 6 supervoltage x-ray machines in the 1–2 million voltage range, proton beams of 1–6 million volts and 'nothing else in the way of equipment be supported.' In retrospect, conspicuously absent was any mention of telegamma megavoltage therapy (155).

After discharge from the Army in March, 1947, Fletcher planned to spend 9 months in London, Manchester, Paris, and Stockholm for additional radiation therapy training. Before he left, his wife arranged an interview with Dr. R. Lee Clark (1906–1994), who shared with her a background in Mississippi, and who was the director of a fledgling and rudimentary new cancer hospital in Houston, Texas. By agreement, Fletcher then sent progress reports back to Dr. Clark concerning what the major European cancer centers were doing. On 1 October 1947 a financial commitment was extended to Dr. Fletcher in the form of a traveling fellowship. When Fletcher returned to Houston in January, 1948, for another interview, he was hired (16 January 1948) to head the radiology department of the relatively primitive cancer hospital (151, 156–158).

Munroe Dunaway Anderson, a bachelor, died in 1939, leaving a $20 million Foundation (trust fund). The state of Texas had wanted to build a cancer hospital since 1941, but lacked funds. In 1942 the State and the University of Texas joined with the Foundation in creating the University of Texas M.D. Anderson Hospital and Tumor Institute (MDA). On 16 May 1942 the M.D.A. Foundation acquired the Houston estate of a deceased Col. James A. Baker, who had bequeated it to Rice University which is located just across the street. In December of 1942, a five-person staff began research work there. In 1943, 11 physicians were hired to unitize 22 inpatient beds at nearby Herrman Hospital. In March, 1944, the first outpatient clinic was established. In 1948, after G.H. Fletcher started work there, 12 former Army surplus buildings were moved to the Baker estate grounds to house the burgeoning staff and equipment in less than opulent quarters. Ground was finally broken in December, 1950, for a modern hospital and research facility; but the Korean War (25 June 1950) delayed completion until March, 1954 (151, 156–158).

During his fellowship in Europe in 1947, Dr. Fletcher had made contact with UK physicist L.G. Grimmett of teleradium fame. Dr. Fletcher lobbied Dr. Clark for the hiring of Grimmett as department radiation physicist, and to help develop a telecobalt unit. Dr. Grimmett inaug-

Fig. 3. Design plans for joint venture, 1949–1950. Pictured left to right are: Dr. R.L. Clark, Dr. M. Brucer, physicist L.G. Grimmett, unknown, Dr. G.H. Fletcher.

urated the physics department at MDA in February of 1949. Work was started immediately toward machine design and toward obtaining a source (65). It was necessary to get the cooperation of the Atomic Energy Commission (AEC) in order to obtain a cobalt source. Dr. Shields Warren, by then director of the Division of Biology and Medicine of the USAEC (a position similar to Dr. Cipriani's in Canada), believed that a 1 000 curie cobalt source was not feasible for a therapy unit. He cited U.S. Navy difficulties in shielding only 100 curies of cobalt. Dr. R. Lee Clark, however, was a member of the medical board of the Oak Ridge Institute of Nuclear Studies (ORINS), a non-profit educational corporation comprised of southern universities and newly organized to make AEC facilities available to these civilian institutions (24, 151).

The AEC and ORINS

On 1 January 1947, the super-secret Army Manhattan District had become the civilian-controlled AEC, which then controlled the Oak Ridge reactor and made isotopes for the public and bombs in secret (24). The AEC in 1947 authorized three hospitals for research in the use of radioisotopes in treating cancer. In addition to ORINS in Knoxville, Tennessee, radioisotope research hospitals were approved in 1947 for Brookhaven, NY, and Chicago (Argonne). Marshall Brucer, M.D. (1913–1994), had been appointed research chairman for the new ORINS Medical Division in December, 1948. He had previously been working as a physiologist at the University of Texas at Galveston (UTMB) (4, 24). Dr. Clark arranged for a dialogue to begin between Dr. Brucer and L.G. Grimmett in the summer of 1949 (152). By August of 1949, Grimmett had a tentative telecobalt design which he presented to Brucer at ORINS. By September, 1949, Drs. Clark and Brucer were proposing collaboration on telecobalt. Dr. Brucer visited MDA in October, 1949. In November a proposal for the coordinated project was sent by Clark to Brucer. On December 19 and 20, Drs. Clark, Fletcher, and Grimmett traveled to ORINS to present their joint proposal for building a telecobalt therapy unit to A.E.C. officials: Holland, Lough, Woodruff, and Aebersold (152, 155). The proposal was made 20 December, 1949, and a formal contract was drawn up and presented to all parties in January, 1950. This formalized the A.E.C.-ORINS-M.D.A. cooperative venture (155), Fig. 3.

On 9 January 1950, sixteen 10 curie sources of cobalt-60, which Paul Aebersold (Ph.D. Berkeley, 1939) had scattered around the edges of the Oak Ridge reactor as extra shielding because they sucked up so many neutrons, were removed to begin dosimetry measurements (24).

After the meeting at Oak Ridge and the approval of Dr. Grimmett's preliminary design as meeting AEC safety and handling requirements, the AEC then asked for a meeting in Washington, DC, to see how many institutions would be interested in such a unit. Thirty-three physicians, physicists, and vendors attended the meeting on 13 February, 1950, to discuss 'multicurie cobalt-60 teletherapy sources' (155). Representatives from GE, Allis Chalmers, Kelley-Koett, and Westinghouse, the AEC, the Universities of Chicago, California, Minnesota, Western Reserve, and Temple, the Mayo and Cleveland Clinics, the LATI, MD Anderson, New York City Hospitals, Cook Co. Hospital (I. Hummon), Memorial NY, NY, Chalk River (M. Thomas), and Saskatchewan (H. Johns) were present.

Dr. Brucer said that he chose this group of 'unbiased' experts because he knew that they would all agree to the project and he needed all the scientific backing he could get 'to expose humans to unheard of cobalt-60 atomic radiation'. There was, however, a serious cobalt-60 production problem because the American reactors had been preempted for plutonium weapons production (24).

Physicists Aebersold and Lough from the AEC told the group that the 'ultimate maximum specific activity to be expected from the Oak Ridge reactor would be 2 curies per gram'. And they added that cobalt-60 deliveries could in no way be guaranteed because medical isotopes were given low priority. By contrast, Mr. M.H. Thomas, Chief of the Radioisotopes Branch at Chalk River, Ontario, stated that the NRX (Canadian reactor) could produce an activity of approximately 13 curies/g at 24 weeks, 27 Ci/g at 48 weeks, and 39 Ci/g at 72 weeks. He also noted that the Canadian AEC would consider the activation of any special cobalt sources submitted to them, but the maximum diameter would be 1.6 inches. He noted that currently there were cobalt-60 sources being activated at Chalk River that were due for completion in February, 1952. These sources were in the form of discs which were one inch (2.54 cm) in diameter, weighed 2.31 g each, and were expected to reach an activity of 18 to 40 Ci/g. He also stated that the Eldorado Co. was planning to market a 1 200 curie

Fig. 4. Final inspection of the Grimmett-designed unit, June of 1951. Pictured left to right are: Dr. G.H. Fletcher, Dr. M. Brucer, and G.E. physicist Dale Trout.

cobalt-60 medical unit at a cost of $25 000. A rough sketch was shown, with no internal details (155).

Physicist H.E. Johns stated that his design for a cobalt-60 irradiator was generally similar to Dr. Grimmett's. Mr. Dale Trout, General Electric X-Ray Corporation, mentioned the cost of the GE one and two million volt x-ray therapy units as $68 000 for one MV, and $120 000 for two MV. He said that in view of the Canadian estimate of a $25 000 cobalt machine, his company would be very much interested in constructing such devices. After the meeting, plans were made to contract with GE to produce the Grimmett design and to contract with Chalk River to activate a high intensity source of 1 250 curies (152).

Later that night the Canadians and Americans discussed the details in Grimmett's hotel room (24). The Canadian reactor would need modification to handle such high intensity sources. And each source would have to be large enough to contain 1 000 or more curies, but small enough for therapy and machine requirements. Sprawled on the hotel room floor arguing gamma yield for various source sizes, Grimmett and Brucer threw out a half-dollar and a dime for discussion. Harold Johns, who paid the bellboy for beer and had a quarter (2.4 cm) in change, threw it down. Johns would later use the Chalk River disc size of 2.54 cm diameter by 0.5 mm thickness. His machine ended up with a source volume of 2.54 × 1.3 cm (presumably 26 discs), a mass of 40 g, and a specific activity of 25 Ci/g (145). The American source would use four square wafers each 2 × 2 × 0.25 cm for a volume of 2 × 2 × 1 cm (159). Different source sizes were later modified so that they would fit into a standardized source container (160).

American effort thwarted

After reaching agreement with Chalk River, Dr. Brucer then had the unenviable task of explaining to the AEC why ORINS wanted to import radioactive isotopes from Canada. He swears that at one point (April, 1950) he had to swear to the United States government that he would not disclose any secrets about Canadian cobalt-60 to Canada (24)!

In May of 1950, L.G. Grimmett presented a paper and an exhibit illustrating the '1 000 Curie Cobalt-60 Irradiator' at the MDA fourth annual Cancer Research Symposium (65, 151). This paper was published later in 1950 (68). In June, 1950, the Korean War started. This held up construction of the MDA facilities. Also, Dr. Grimmett had planned to use uranium shielding in the cobalt head, but due to wartime restrictions, he had to switch to the tungsten alloy Hevimet, which was hard as diamond and difficult to machine. ORINS obtained the cobalt-59 wafers, and they were inserted at Chalk River in June, 1950, along with the two Canadian sources (Johns' and Eldorado's) (24, 65, 151, 161).

In July of 1950 the final contracts were completed and signed between UTMDA and ORINS and between UTMDA and GE (155, 161). In July Dr. Fletcher presented a paper in Paris at the Fifth International Cancer Congress detailing the design and operation of the unit (151, 162, 163).

The GE unit and the Chalk River source had both been expected to be ready in one year, by June of 1951. Just days before the cobalt machine was completed by GE in Milwaukee, L.G. Grimmett (1902–1951) died unexpectedly on 27 May 1951. After a final inspection in June by Drs. Fletcher and Brucer, Fig. 4, the Grimmett-designed unit was shipped to ORINS to receive a source (24, 65, 151, 161).

Between June and August, 1951, Chalk River sent out two 1 000 curie sources; one to W. Adair Morrison of the Radiology Branch in the National Research Council at Ottawa, and the other to H.E. Johns. The American source had measured only 650 curies and so was reloaded into the reactor for another year. It was finally removed in July, 1952, with an activity of 876 curies, and a specific activity of 25 curies/g (161). Records at M.D. Anderson state that the source was withdrawn from the Canadian reactor 'for a time in order to accommodate military priorities' (151).

Meanwhile in August, 1951, the source for Saskatoon was installed immediately in the Johns machine, which was

then tested until October. Treatment began in Saskatoon on 8 November. Physicist Johns reported a dose rate of 33 roentgens per min at 80 cm SSD or 84 r/min at 50 cm (145). The Eldorado source was tested first in Ottawa, then shipped to Victoria Hospital in London, Ontario, for immediate clinical use on 27 October 1951.

In August of 1951 the GE unit, which had been sent from Milwaukee to ORINS, was loaded with a 200 curie source loaned back to the AEC by Dr. Max Cutler of the Chicago Tumor Institute (65, 151). With this source the unit delivered 15.5 r/min at 50 cm SSD for a 15 × 15 cm field (159, 161).

Finally in July, 1952, the USA source, now at 876 curies, was released from Chalk River to ORINS (65, 161). Fourteen months of testing at ORINS ensued. At 50 cm SSD the output was 77.3 r/min for a field 20 × 20 cm. Depth dose data for this unit and for the two in Canada was reported as essentially identical, and comparable to a 3 MV x-ray unit. The source wafers needed to be thinner (0.1 cm) and smaller (1 cm). The optimum shape for the source capsule was found to be a cylinder rather than a square box. And it was recommended that the source strength be at least 1 500 curies with a specific activity of 50 curies per g (161).

The Korean War had delayed construction of the M.D. Anderson Hospital. In September of 1953, the cobalt machine was finally trucked the 983 miles to Houston (151), as the shielded basement quarters for the therapy department were nearing completion. Testing was completed and treatments started in February, 1954, a few weeks before the final move from the Baker estate to the new MDA hospital on 19 March 1954 (151, 158). By January of 1955 the output was only 32 r/min at 70 cm, and over Thanksgiving, 1955, the source was replaced by one of 2 000 curies (164). In 1957 MDA bought a rotating unit from AECL and commenced treatment with it in September, 1958 (151, 165).

Postscript

England's J.S. Mitchell, M.D., Ph.D., could not get cobalt-60 (his idea) from Harewell, ARE, so he persuaded his physics colleague at Addenbrooke's Hospital, Cambridge, H.F. Freundlich (who had also served in Canada) to try a radio-iridium telegamma unit in 1949–1950. With a half life of 74 days and maximum output of 16 r/min at 8 cm, it was more like teleradium than telecobalt (166, 167).

General Electric never made another cobalt machine. The GE marketing people did not think much of the idea and predicted only ten units would be sold in the next ten years. See Table 5. Even in 1956 some were of the opinion that 250 KV units would never be replaced (24).

On 3 October 1953, at ORINS, Dr. Brucer announced that the AEC and ORINS were not in the x-ray business and did not intend to get into it (155).

Johns sold his design to Piker (4). Don Green of CPD helped develop the rotational unit (165) for AECL and then joined Piker X-Ray in Cleveland (7).

Marshall Brucer retired from ORINS in 1962 with multiple sclerosis and then survived another 32 years, writing and publishing to the end (24), on a motorized wheelchair, with a Foley and a personal computer, working at his home in Tucson, in rooms lined from floor to ceiling with books and documents (personal interview, Tucson, March, 1993).

Dr. Gilbert Fletcher with an abundance of clinical material and a genius for organization and technique went on to publish (among other things) a wealth of clinical data on the use of telecobalt (168). Like Henry Ford and Robert Fulton, he was not primarily responsible for the invention of the machine which brought him celebrity. However, his name will forever be linked with its development and use as one of the most successful and practical anti-cancer therapies of its time.

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