# A HISTORY OF THE DEVELOPMENT OF X RAYS FOR USE IN RADIOTHERAPY (1896-1960)

E. Aird[1]

[1] Emeritus physicist, Newcastle General Hospital, Department of Medical Physics, Newcastle-upon-Tyne, England;
Emeritus physicist, St. Bartholomew's Hospital, Department of Medical Physics, London, England;
Emeritus physicist, Mount Vernon Cancer Centre, Department of Medical Physics Northwood, England

*Abstract*— **The development of x-ray equipment for radiation therapy over the time from 1896 to 1960 is discussed. Over the years, equipment evolved from generating energies of 10 – 100 kV to 1 MV, and then 4 MV. Descriptions of specific devices such as the St. Bartholomew's (Barts) Hospital 1 MV unit, that were innovative at the time, will be presented.[a]**

*Keywords*— **early radiotherapy, x-ray therapy, megavoltage, history of radiotherapy equipment.**

## I. INTRODUCTION

This article will study the history of x ray production and its uses in external beam radiotherapy from 1896 until 1960. It will describe briefly the early years, when treatments were mainly on an empirical basis and often based on skin reactions. Then, during the 1920s-1930s, there was more understanding of the biological processes involved, and multiple fractions of dose were given, which allowed more effective dose to the tumour. However, even at this time the energies of x rays used (expressed in kV here) were only 10-100 kV, which could only be used for skin tumours and very superficial cancers. The higher energies, available only from the end of this period (200-300 kV), gave some advantage; and were used throughout the period 1930-1960 for "deep X ray" (DXT) therapy. But even so the depth doses were poor and could only be successful for tumours at depths of 10 cm if combined fields were used, (see Figure 1.)

It became obvious that much higher energies were needed (see history paper by FT Farmer [2]). The attempts at attaining these energies (above 300 kV initially; then to 1 MV and above) are outlined; in particular the development of the 1 MV x-ray set at St Bartholomew's Hospital and its use (1938-1962) will be described in some detail: as an extraordinary example of electrical engineering and understanding of the physics involved.

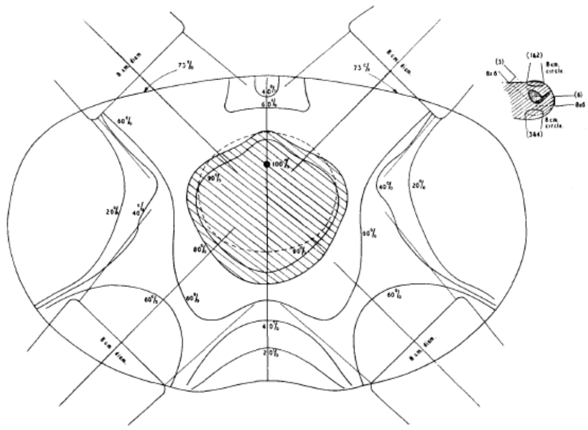

Fig. 1. A treatment for bladder cancer with 250 kV using 6 fields: the small figure at top right shows the orientation of the fields. [1]

Then in the 1950s, physicists and engineers were looking at different ways of obtaining higher energies, in particular: the Van de Graaff generator (typically 2 MV) and the use of the high energy radioactive source: Cobalt 60. Alongside these developments came the development of linear accelerators both in UK and USA using the acceleration of electrons by microwaves. The very successful 4 MV Mullard accelerator installed at the General Hospital in Newcastle-upon-Tyne (1953) will be described in detail.

## II. THE VERY EARLY HISTORY OF RADIOTHERAPY

There were various attempts from 1896 to 1910 (all very empirical) by medics of various disciplines to try to make use of the therapeutic benefits of x radiation. [3] These were mainly making use of the caustic effects of radiation (first noted by Pierre Curie with radium: the state of his hands was noted at the joint lecture he gave with Marie Curie at the Royal Institution in 1903). There was no real understanding and particularly no attempt to quantify the amount of radiation given (although times of exposures were recorded.). Many of these "experimenters" would give very large

[a] The author worked with Professor Frank Farmer at the Newcastle General Hospital starting in 1967. He designed the thimble chamber that replaced the original Farmer chamber and is used widely to this day.

radiation doses in the hope of achieving the same results as surgery: the complete destruction (extirpation) of the tumour.

Fig 2. Very early use of x rays. Patient treated at St Bartholomew's Hospital circa 1915. Note the lack of protection.

*A. The low X-ray energies at that time:*

The term "low energy" or "soft" referred to radiation of 100 kV or less with little or no filtration where the x-ray set was used at very short distances.

A doctor who used these x rays successfully was Dr Chaoul [4,5] in Berlin in the 1920s and 1930s. He used short–distance low-voltage x-ray therapy, with x rays of HVL 0.3-2.5 mm Al at 45-50 kV (see SXT section below). He achieved good results (mainly for skin cancers) using a daily dose of 300 to 500 R[b] (the unit of "dose" by then in use) to a total dose of 6000-15,000 R. It was only in these later years (after ICRP 1928 [6]) that R, as a unit of dose, became commonly used.

Prior to this, various methods were used to give a measure of the amount of radiation given including pastilles and "radiometers". However, it was particularly the observance of the skin reaction to various levels of x radiation that most clinicians used to judge the amount of radiation to give to a patient.

*B. Measure of Skin Erythema*

The first published case of an X-ray burn appeared in April 1896. By 1897 experiences with X-ray burns were being widely published, and by 1900 at least 170 cases of X-ray burns had been documented. In 1902, Dr. G. E. Pfahler, Assistant Chief Resident Physician and Skiagrapher to the Philadelphia Hospital, reported that "Nearly everyone who makes frequent fluoroscopic examinations or demonstrations with x-rays suffers more or less from a dermatitis of the hands". [6]

Dr Finzi looked at "Late X-ray and Radium effects". [7] In particular, he documented late skin effects including a) telangiectasis at 1-3 years; b) pigmentation occurring almost in every case where erythema has been produced; c) atrophy and thickening of the skin; and d) the later production of benign or malignant neoplasms. He also states: "my own fingers are an example of chronic radio-dermatitis" (from his radium exposure 1911-1912).

Figure 3 below shows the results of Hausser and Schlechter ("The skin erythema dose as a biologic effect of radiation") when they investigated erythema following Grenz ray exposures. [9]

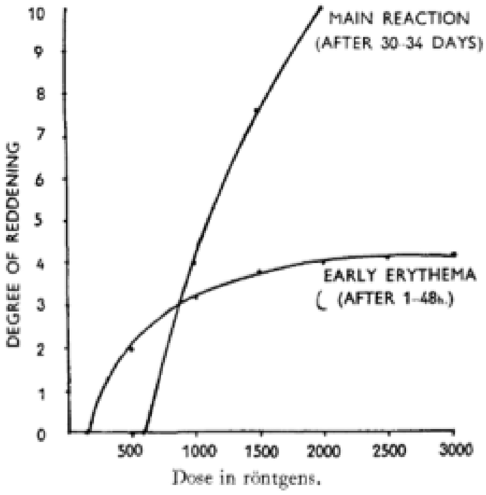


Fig. 3. Relation between Dose and Erythema

**A** paper from the Middlesex Hospital, London in 1935 linked x-ray treatment experiences to those of radium by describing the use of the "Radium Bomb", which held 2 grams of radium. [10] They measured dose rates of 18.3 R/min at 3 cm and stated: "It appears that at a radium to skin distance of 3 cm a skin erythema appears after 6 hours (6600 R), and that skin peeling occurs after 7 hours (7700R)". Interestingly, they also quoted R. Paterson and H.M. Parker as having found only 3000 R was required for erythema and 4000 R for skin peeling. [11] This demonstrates how uncertain skin erythema was as a measure of dose.

*C. Very low energy Radiotherapy 10-50 kV.*

It is interesting to link Chaoul's work [5] with the later use of "contact" radiotherapy. The term "The Contact Set", was used by Philips for their low energy unit used from the 1960s to the 1980s which had a target at 2 cm from the x-ray window (see Fig. 4). With a short FSD (5 cm) the dose at 2 cm depth was only 30- 40% [12].

A "Contact Unit" (that gave similar depth dose) was developed by Philips in the 1950s. This was the RT 50; with

[b] Approximately 3-5 Gy in today's unit of absorbed dose

only about 2 cm from the anode to the skin (FSD). This unit was also used by Papillon [13]. (See Figure 5).

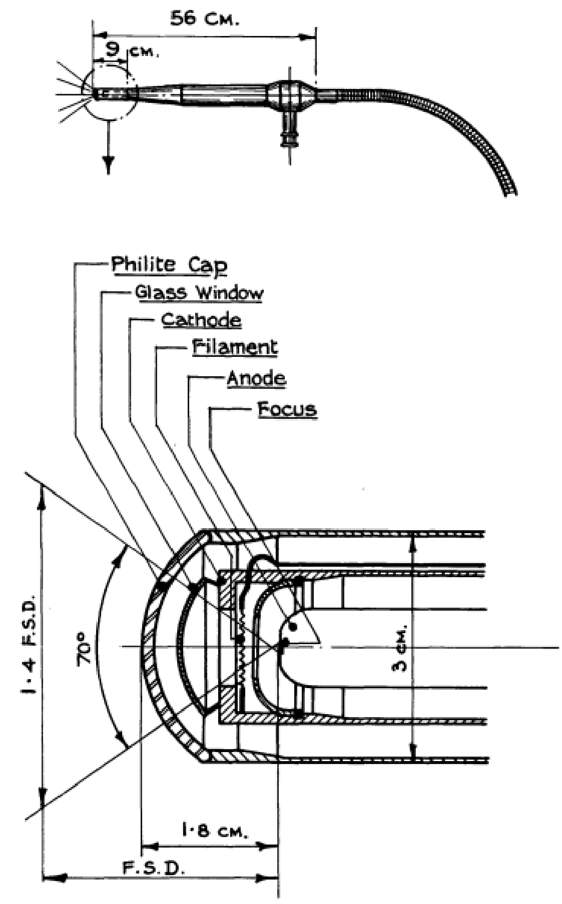


Fig. 4. Sectional view of Philips Metalix tube; installed in the Royal Cancer Hospital. See P.A. Flood and D.W. Smithers. [14]

The modern Papillon unit replaced the earlier Contact Unit for rectal cancer treatment according to a recent paper. [15] The depth doses in the 1910s would have been a little different depending on the stand off from the skin surface. The Papillon is an updated "contact" set; other new systems use miniature x-ray tubes that can be used interstitially particularly for intraoperative radiotherapy. [16]

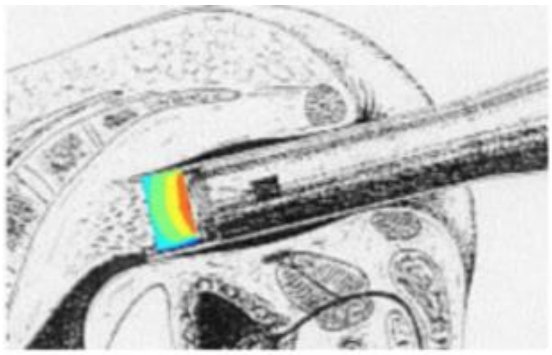

Fig 5. (Upper) The Papillon x-ray machine (Manufactured by Ariane Medical Systems UK). (Lower) The use of the Papillon x-ray applicator /tube to treat a rectal cancer.

## III. THE NEXT PHASE IN X-RAY RADIOTHERAPY: 1920-1950

Several papers have been published in BJR (1928 to the present day); the original "Archives of the Roentgen Ray (UK)" (1897-1927); and the American Journal of Roentgenology (from 1907) that describe some of the uses of radium and x rays between 1900 and 1920. Most of these are from a surgeon's perspective, so give little in terms of the equipment used and their characteristics.

For example: the use of 200 kV x rays in lung was described in 1928; and in the breast in 1926 using 220 kV (G Keynes particularly, see [17,18]). But there is no definite foundation for radiotherapy given; particularly because there was no system for measuring the "dose" given. Uncertainty in dosimetry led to widely variable results until the introduction of the unit of exposure: the Roentgen (ICRP 1928).

It is also possible by looking through the early issues of BJR for 1928-1935 to find articles, many from clinicians and surgeons, that describe their use of radium and x rays to treat various disease, and Mould has written extensively about the use of radium from 1895 to 1937. [19]

### *A. Radiotherapy x-ray Equipment*

In the period 1896-1913 X-ray energies of only 50-100 kV (cold cathode, Crookes tubes) were available, and they operated at only a fraction of 1 mA, so exposures were impractically long, sometimes several hours. [20] At this time radiologists were using the same equipment but with important differences: short exposures at high mA compared with long exposures for radiotherapy at low mA and they referred to the "hardness" of the beam as measured by a spark gap. Fig. 6 summarizes very recent work to link the published spark gap values to kVp in radiology. [21]

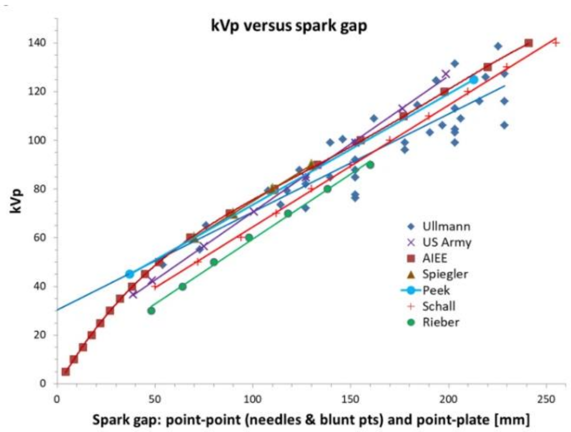


Fig. 6. The relationship between kVp and spark gap distance. [21]

*B. The importance of the Coolidge tube*

The early "gas" tubes (see the extensive MPI article: 2018 Rolf Behling, Philips Healthcare [22]) were erratic and unreliable and operated at low power. An important change happened with the advent of the *Coolidge tube* with its hot cathode [23] that promised huge benefits both in terms of mA and reliability. See Fig. 7 and Mould 1995. [24, 25]


Fig. 7. A Coolidge x-ray tube (University of Melbourne Museums Collection)

*C. Equipment for low-medium energy x rays*

It is possible to summarize in a table the properties of the equipment used in the range of x ray peak voltages from 10-400 kV. These are: 1. Grenz rays (10 kV); 2. Superficial x rays (SXT: 50-150 kV); and 3. Deep Therapy x rays (DXT: 200-400 kV). The contact unit and its development by Papillon was described above.

Table 1. Characteristics of equipment operating from 10 kVp to 400 kVp.

| Name | Energy | HVL | % depth dose |
|---|---|---|---|
| Grenz | 10 kV | <0.03mmAl | 100% at surface |
| SXT | 50-140 kV | 0.5-5mmAL | 80-95% at 5 mm |
| DXT | 150-400 kV | 7mmAL-4mmCu | 50% at 60-80 mm |
| Contact/Papillon | 50 kV | 0.6-1.3mm Al | 100% at surface |

*SXT***.** Many of these sets in the 1950s and 1960s were provided with a range of "energies", from very light filtration (HVL 1mm Al) to high filtration (140 kVp and HVL 8mm Al). It was in the late 1920's that HVL began to be used as a measure of beam quality: for lower energies mm Al is used; for higher (DXT) energies, mm Cu is used. The table shows the HVL in mm Al and the percent depth dose, to give an indication of the penetrating power of the different energies. There is another factor that determines the depth doses: the Focus-Skin-Distance (FSD).

*C (1). SXT*

An SXT unit available in the 1960s was the Watson ST 150 (see Fig. 8) [26]. It could produce x rays in the range 50-140 kVp at currents from 5-10 mA. The tungsten target angle was much shallower than that used in radiology, because there was no need for "sharpness".

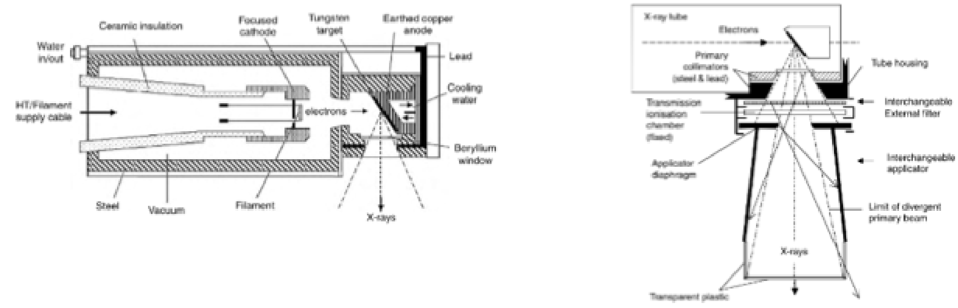


Fig 8a. The Watson ST 150 tube. (L) The x-ray tube showing its components. (R) The components used to collimate the x-ray beam.

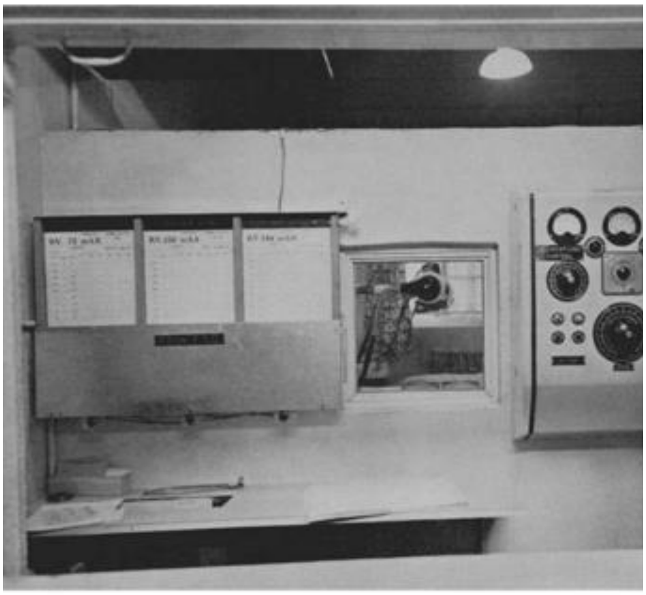

Fig. 8b. SXT Unit Viewed through a lead glass window, with the x-ray control unit on the right.

*C (2). The use of SXT for Radiotherapy*

An important use of SXT was for skin cancers; either basal or squamous cell. It still is today, although radiotherapy centres without SXT use electron beams from linear accelerators. [27] SXT equipment was provided with a choice of filters to produce appropriate depth penetration at different kV. At 50 kV the depth dose is less than 50% at 5 mm while at 100 kV depth dose is 75% at 5mm. Applicators were used to fix the distance between the focal spot and the skin and to limit the dimensions of the beam. Lead masks, typically only 0.5 mm of lead, would provide very good shaping of the x-ray beam to the area of tissue to be treated. Generally, for 1-2 mm deep lesions 75 kV would be used; for lesions of 3-5 mm 100 kV is applied. For even thicker tumours 250 kV (see "orthovoltage" below) would need to be used.

*D (1). Deep Radiotherapy Tubes*

Tubes for "deep radiotherapy" initially had energies of 180-250 kV, then later these voltages were extended to 400 kV.

The Marconi DXT unit at Newcastle-upon-Tyne, Regional Radiotherapy Centre, under the direction of Professor Frank Farmer, operated at 250 kV, 15 mA with heavy filtration yielding an HVL of 3.5 mm Cu but an output of only about 30 R/min) balancing the gain in depth dose with longer treatment times.

The high continuous current at 250 kV produced an enormous amount of heat in the target so continuous oil cooling was necessary. The hot oil then was cooled in a heat exchanger using continuously flowing water. The target angle was 45 degrees, focus to skin distance was 50 cm.

The filtration could be varied and frequently involved the use of a Thoraeus filter in which combinations of Al, Cu, and Tin were set in the correct order so that the characteristic x rays from each metal were advantageously absorbed by the next filter [28].

It is essential to arrange the materials in the correct order, with tin closest to the x-ray tube. See Fig. 9.


Fig. 9 (a). DXT x-ray tube photo

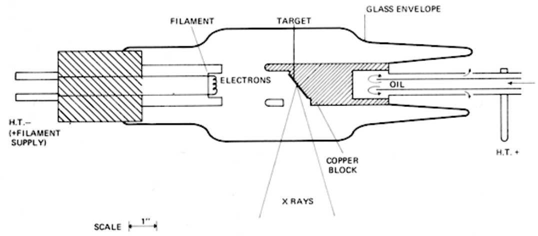


Fig. 9 (b). Diagram of DXT tube

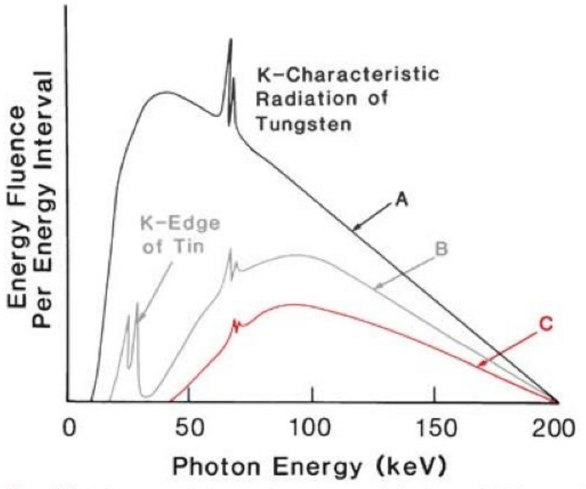


Fig. 10. Schematic graph showing changes in spectral distribution of 200 kVp x-ray beam with various filters. Curve A is for an Al filter, curve B is for a Sn + Al filter, and curve C is for a Sn + Cu + Al filter.

DXT equipment was used for all deep-seated tumours in the 1930s-1950s before higher energy equipment became available. After the advent of high energy treatment machines (Cobalt 60 and linear accelerators, which could penetrate much further into tissue with HVL varying from 100 mm to 150 mm of soft tissue) DXT was used only for palliative treatment in the lungs and for deeper superficial cancer not suitable for SXT.

*D (2). Medical Use of DXT*

The lack of penetrating power of 250- 300 kV (50% dose at 7 cm depth in tissue) made it difficult to treat the abdomen; these energies had to be used with multiple fields (see for example Fig. 1 showing a rectal treatment); palliative lung treatments also were given. Post mastectomy treatments of the chest wall were given using this energy of radiation.

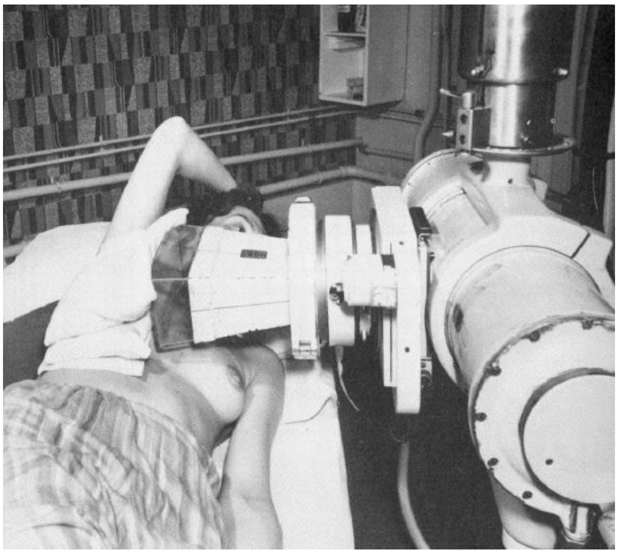

Fig. 11. 250 kV DXT unit Treatment of Breast (Courtesy C Orton).

## IV. Radiotherapy delivered through multiple fields using manual treatment planning

To achieve a higher dose at the tumour than at the skin surface several fields would be used. But with only manual treatment planning available to combine isodose curves together, this was a time-consuming activity.

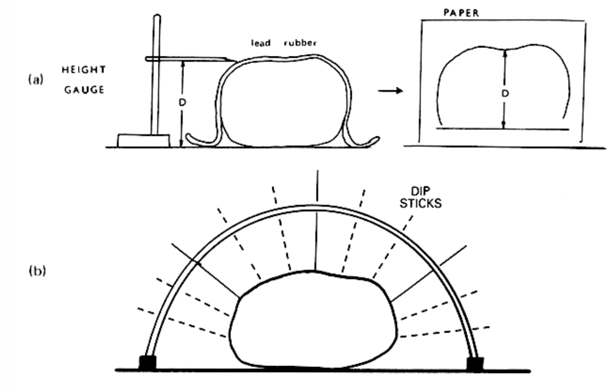


Fig. 12. Tools for hand-planning: (a) Stiff lead-impregnated rubber to take the patient outline at the appropriate cross section, plus a height gauge. (b) An alternative method of obtaining an outline with "dipsticks".

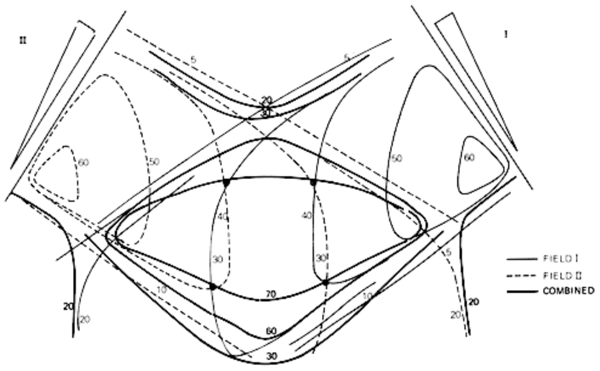


Fig. 13. An example of two wedged fields hand planned to give the combined dose distribution

The early days of computers had the potential to make this much easier. But in the 1960s only large computers in universities could perform these complex calculations. For example, WV Mayneord introduced "An electric adding machine and its uses in radiation therapy". [29]

Then the era of mini- computers meant that hospital physicists could develop their own programmes to perform these calculations [30, 31, 32]. A major breakthrough was achieved by Bentley and Milan who developed a system to be used on a PDP-8I (DEC) mini-computer within the radiotherapy/medical physics department. [33, 34]

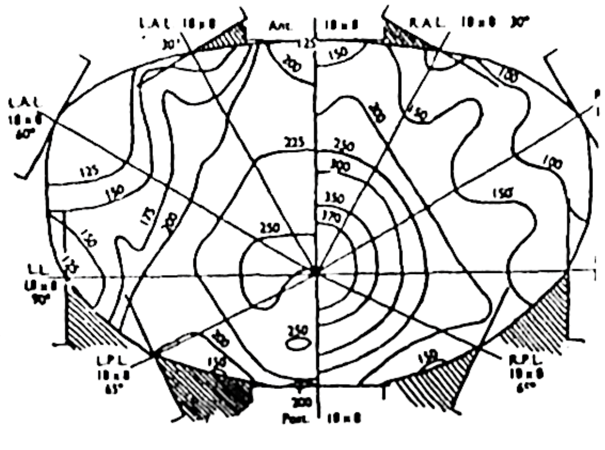

Fig. 14. More complex plan: Combined isodose curves for radiotherapy of cancer of rectum. (L) 200 kV (HVL 2mmCu) 40 cm FSD, 8 fields of 18x8 cm. (R) 1MV with 100 cm FSD, 8 fields 18x8 cm. [46]

### *A. Depth Dose and isodose*

The Hospital Physicists Association (HPA) was very involved with collecting sets of measurements from physicists around the UK, thus helping physicists working alone in many smaller centres. The BIR picked this up and started producing tables published in supplements 5, 10, 11 and finally 25 of the BJR. [35]. It is fascinating to find researchers still interested in this subject: Tze Yee Lim et al [36] reported a range of film measurements for these energies: 75 kV, HVL 2.2 mm Al; 125 kV, HVL 3.5 mm Al and 250 kV, HVL 1.3 mm Cu; from an Xstrahl 300 kV x-ray set. They found the results "were consistent with BJR 25 ". For example, the average deviation at 250 kV was -0.1–2.0%. For those interested she also produced some very nice graphs of SXT/DXT depth doses vs electron beam depth doses.

## V. THE NEED FOR VOLTAGES HIGHER THAN 250 KV

### *A. The characteristics of the ideal energy of x rays for deep-seated cancer.*

Discussion at the time suggested that the ideal beam energy would have the following characteristics:

1. Sufficient depth dose at 10 cm depth - at least 50%;
2. Sufficient scatter to add to primary;
3. But not too much scatter outside the geometric edge of the beam giving unwanted dose;
4. Some skin sparing; and
5. Bone sparing.

### *B. The search for high energy x rays: the US experience*

By 1933 a few experimental high-voltage x-ray devices had been constructed in the USA, operating at voltages up to one million eV, but they were too unreliable in operation to give clinical results which could be properly assessed.

Some examples of high energy X ray attempts can be drawn from "The race for megavoltage x rays versus telegamma" by RF Robinson [37] and "The Supervoltage Story" by Schulz [38]:

1) C.C. Lauritsen manufactured tubes at Cal. Tech. which were 30 ft long and used GE transformers in series. He also developed a 13 ft tube with high kV generated by a Cockcroft Walton generator that reached 900 kV. In addition:

(a) 600 kV tube at the High Tension Lab. Used by Dr. A. Soiland [39] 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 were made and sold commercially by Kelley-Koett in 1931: 600 KV for Harper Hospital in Detroit [40]. Also:

(e) 1933: 650 kV for Lincoln General, Nebraska.

(f) 1936: 600 kV for Miller Hosp., St. Paul. Minn

### *C. John Read's experience] at Cal Tech in 1932-1934 with the Kellogg set [41,42*

Fig. 15 shows a sketch of the Kellogg system. Powered from twin transformers (each capable of 1000 kV), Read writes of this complicated story "After weeks of (tube) conditioning it was ultimately possible to operate at a potential as high as 1100 kV". The tube was in a grounded steel cylinder. It was surrounded by 2" of lead in the centre. Four apertures in the lead 90 deg apart provided 2 horizontal beams and 2 at about 15 deg below the horizontal.

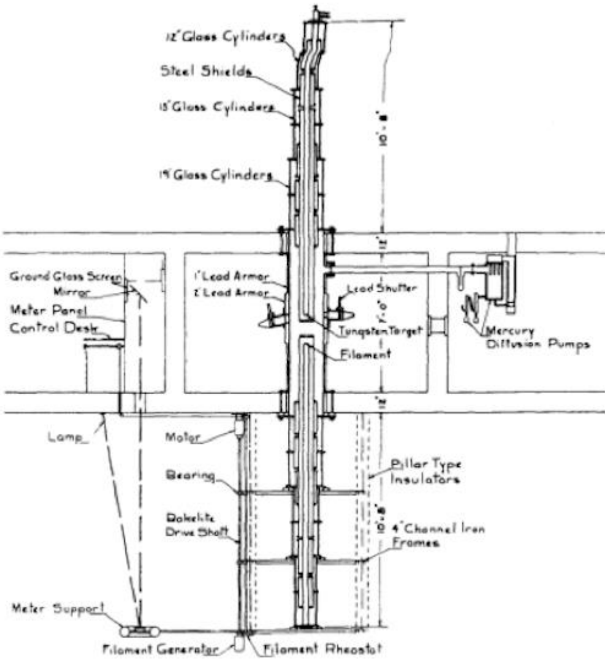


Fig 15. The 1000 kV tube of the Kellogg Radiation Laboratory, Ca Inst of Tech Pasadena (1932).

Control: galvanometer light spots: 1) Pirani vacuum gauge; 2) the current measured by an ion chamber in one of the apertures. The tube voltage calibration was obtained with the aid of a spark gap.

The tube was operated and maintained by post-graduate physics research students. During 1932-1934 (Read's period) the tube worked from 9am until 1 pm for treatments; and the reminder of the day for physics research, 6 days a week. About once a month the filament needed changing.

At a tube current of 3 mA the dose rate was 15 R/min at 60 cm FSD. The beam was heavily filtered with 5 mm steel and 1 mm lead.

An example of a treatment was 8 fields to the pelvis delivering 300 R daily over 8 weeks.

Three patients could be treated simultaneously by using 3 portals from the x-ray target.

Over 3-4 years this unit was used to deliver 11,000 individual treatments a year (approximately:1200 patients).

*D. The "megavoltage" unit at the Netherlands Cancer Institute –Antoni van Leeuwenhoek*

**A** second unit worthy of further description is the one that was installed at NKI in Amsterdam. The "Millionaire" unit operated during the 1950s and had several unusual features. [43]

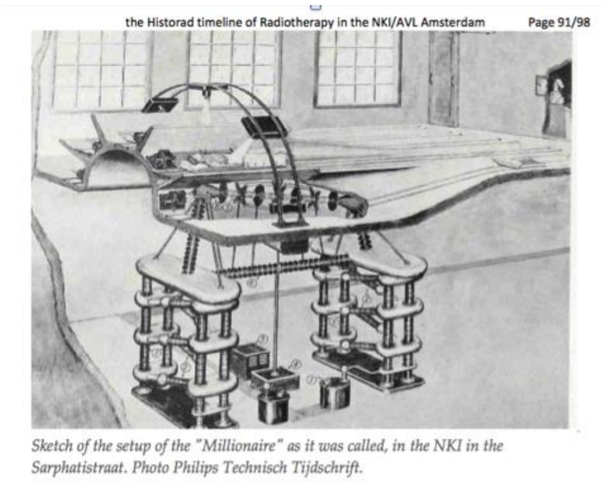


Fig 16 The "Millionaire" Unit at NKI

The "Millionaire" unit is shown in Figure 16. In the cellar stood two cascade rectifiers each of around 600 kV. They were connected to an X-ray tube which was installed up at the ceiling. The machine produced beams in three directions simultaneously through openings in the floor above, so that several patients could be treated at the same time. The positioning of the beams coming up through the floor was particularly difficult and inaccurate.

However, the full potential was not achieved; only 825kV was possible. With kV x rays of this energy, it was found that the radiation dose at depth is not much higher than with the 200 kV radiation which was already available (see Fig 17). Also, there is no skin sparing with 825 kV, and, due to the low beam intensity of 20 R/min, the radiation treatment times were excessive.

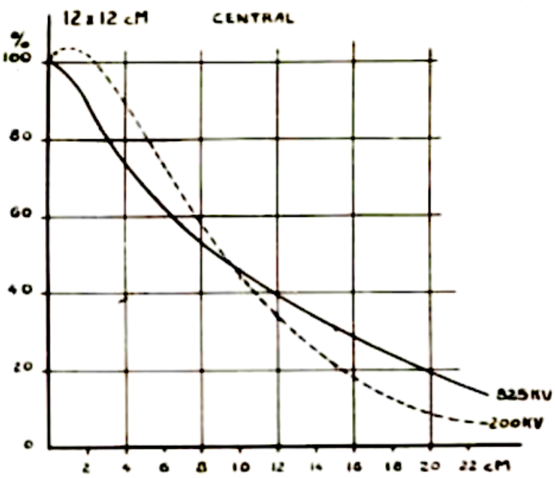


Fig 17. There is a critical balance above 700 kV when side scatter is lower than 200 kV-300 kV, but the penetrating power (the primary beam HVL), is not sufficient to produce a useful depth dose. This can be seen when the depth doses are compared on a graph.

*E. The factors that favour 1 MV vs lower energy x rays.*

These attempts were in good faith; but what wasn't fully understood was that the depth dose is a complicated function of primary beam energy, forward scatter and back scatter. Below 1000 kV there appears to be little advantage in attempting to work with 600-875 kV (NKI), with the added complications of the electronics and insulation etc., compared with 250 kV.

From the experience of the USA and NKI in the Netherlands, several important facts emerged:

1. A most vital point: voltages above 200 kV but below 1000 kV do not give significantly improved depth dose compared with 200 kV (see Fig 17)
2. Significant skin sparing appeared to happen only above 1000 kV
3. Bone sparing becomes significant at 1000 kV

The NKI experience with its 875 kV energy demonstrated the problems with high energy x rays that don't quite reach the critical 1000 kV point.

*E (1). Skin Dose*

The NKI team also noticed that with their 875 kV beam, there was no skin sparing. George Innes noted under the subheading Alteration in Skin Reaction: "Tests were carried out on corresponding skin surfaces on patients with x-ray beams of identical dimensions under the same physical conditions except for the beam qualities. [44] The control beam was one of 300 kV, while the experimental beam was 1000 kV (HVL 10 mm Cu). The dose required in one sitting to produce the same skin reaction was 50% greater with the 1000 kV than with the 300 kV". This is an extraordinary statement given the lack of knowledge at that time but demonstrates the skin sparing of the megavoltage beam.

The term "build-up" wasn't used at that time. The approximate 1-2 mm build-up achieved with the St. Bartholomew's 1 MV set (see Fig. 18) appeared to be sufficient to reduce the dose to the epidermis and to some extent the dermis, markedly reducing skin reaction.

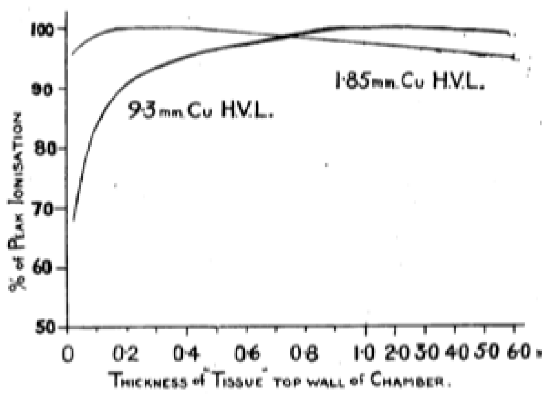


Figure 18. Measurements by George Innes of dose versus depth. [44]

Using existing knowledge of build-up depths (including Cs-137 and Co-60) it was possible to estimate the build-up depth for the St. Bartholomew's 1 MV unit of 0.8 mm. In addition, George Innes measured dose versus the first few mm of depth for the 1 MV beam and a 300 kV beam. (See Fig 18.)

The slope of the build-up curve is rapid to begin with; then, from 95% to 100%, a very slow increase. [45] (see also FT Farmer. [2])

Mayneord (see table below) gives a slightly higher value for the depth of dose maximum of 1 mm.

Table 2. Variation of depth of build-up peak in water with x-ray generating voltage. (From Mayneord, 1950)

| X-ray generating Voltage (MEV). | Depth of maximum dose in water (cm) |
|---|---|
| 1 | 0·25 |
| 2 | 0·5 |
| 3 | 0·7 |
| 4 | 1·0 |
| 6 | 1·4 |
| 10 | 2·6 |
| 15 | 3·5 |
| 24 | 5·0 |
| 31 | 6·0 |
| 35 | 6·3 |

*E (2) Bone sparing*

In a 1962 paper, Farmer demonstrated the lowering of dose to bone as the photon energy is increased. See Fig 19. [2]

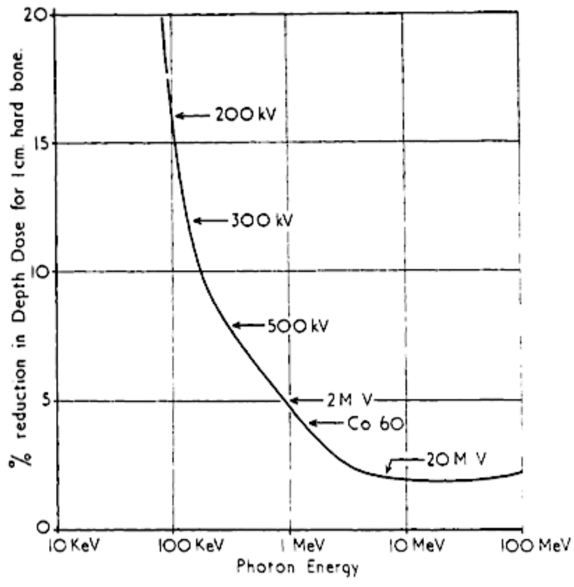


Fig 19 The "shadow" of 1 cm of hard bone for a range of photon energies up to 100 MeV [2].

## VI. THE BARTS 1 MV UNIT (1940S). ST. BARTHOLOMEW'S HOSPITAL, LONDON, (CONTRACTS WITH METROPOLITAN VICKERS FOR A HIGH VOLTAGE THERAPY UNIT POWERED BY COCKCROFT-WALTON CASCADED GENERATORS).

In December of 1934, the Central Research Committee decided to acquire and attempt to operate an x-ray set for radiotherapy at 1MV.

This "Mozelle Sassoon Unit" was officially opened on 10th December 1936, having been funded by a donation of 15,000 pounds from Mrs. Mozell Sassoon. The research department of Metropolitan-Vickers Electrical Co Ltd in Manchester installed equipment to operate at 700 kV in 1936. But the tube became unstable in use [45]. However, by 1938 the plant was operating at 1 MV, and by 1948 then had worked for 10,000 hours (including disruption from bombs and V-weapons!). [46] From a paper given by G S Innes at the Proceedings of the Royal Society of Medicine May 21st 1948 "At the commencement of the war, the department was closed for 3 months, but during the rest of the war, although the department lost its ceilings, windows and doors three times, and part of its roof another time, the plant functioned;…sensitive relays and mechanisms damaged by concussion and vibration being temporarily locked in, by match sticks, until patients' treatments were completed for the day". [47]

Fig 20. The north wing of the St. Bartholomew Hospital where the 1 MV "Moselle Sassoon" unit was installed. The church of St. Bartholomew the Less is visible in the background. (Barts Health NHS Trust Archives)

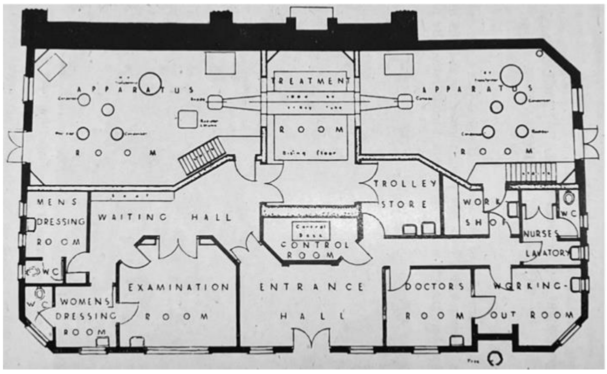


Figure 21. The floor plan of the section of Barts housing the 1 MV unit, showing the treatment room and two rooms housing the generator apparatus. (Barts Health NHS Trust Archives)

### *A. Description:*

The tube was 32 feet long and weighed 10 tons. (See Fig 25 for a diagram of the x-ray tube) The beam could be directed through a range of angles from vertically downwards to 110 deg upwards.

Figure 22. The 1 MV x ray tube at St. Bartholomew's Hospital immediately after installation, showing the couch and its control unit. (Barts Health NHS Trust Archives)

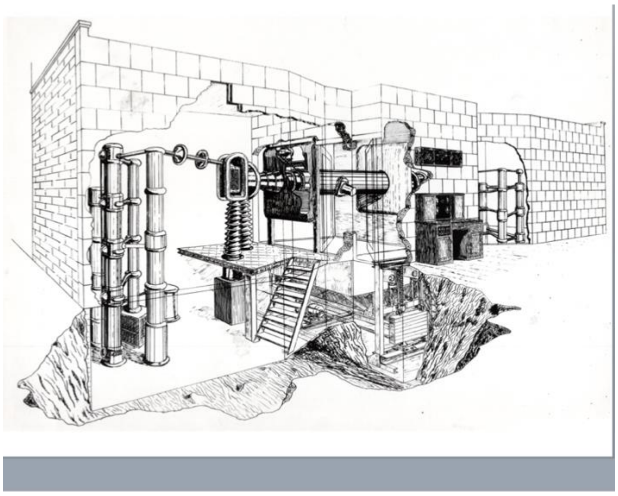

Fig 23. Schematic of generator, tube, and building. (Barts Health NHS Trust Archives)

*A (1). Generators*

The generators for the 1 MV unit were housed in two separate rooms (see Fig. 21). In his 1962 paper Frank Farmer states: "…marked a considerable advance in high voltage engineering… two symmetrically disposed generators giving 500 kV each". [2]

The high voltage was supplied by two 500 kV Cockcroft generators using 4 continuously evacuated thermionic rectifiers, operated from the 3 phase mains. (See Fig 24.)

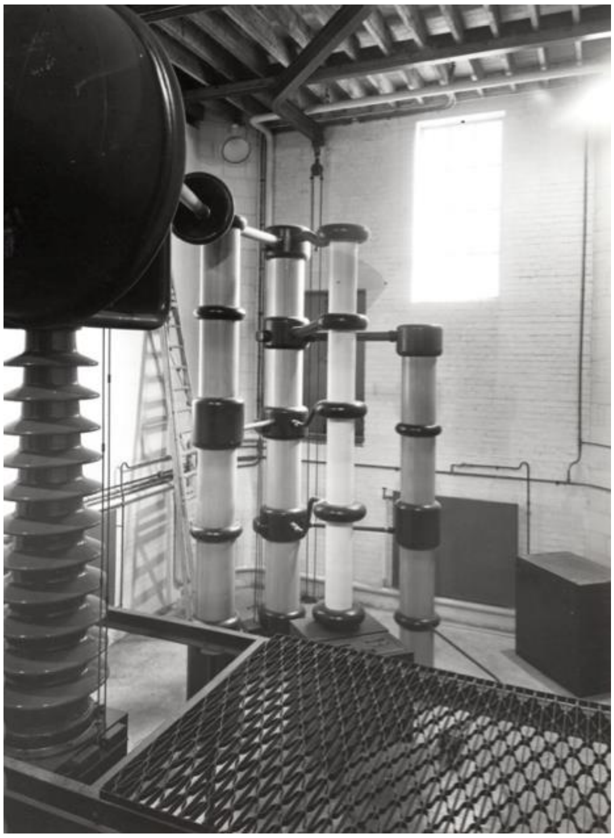

Fig 24. Photograph of one of the 500 kV Cockcroft generators. (Barts Health NHS Trust Archives)

*A (2). Beam Characteristics Limitation*

George Innes wrote "From our early experience with applicators at 700 kV it was apparent that at 1 MV and 1 metre FSD, applicators would be too heavy to handle. An adjustable diaphragm was constructed fitted with a light beam device which indicated the x-ray field size, shape and position." For the time, the diaphragm was a remarkable piece of engineering; it allowed fields of any size from 4x5 cm to 40x40 cm in 1 cm steps. [47]

The adjustable diaphragm also contained a light beam which projected the field size onto the patient's skin.

The depth dose delivered by the 1 MV beam was about 50% at 11cm depending on the field size, and exhibited a build-up region. The 1 MV x-ray energy enabled the treatment of deep-seated cancers which was a major achievement at the time. At the same time, however, the 2.5 cm focal spot resulted in a large geometric penumbra. [47]

The 1 MV Sassoon unit compared favorably with radium which was essentially the standard at the time. According to Innes, the beam was "not quite as hard as the gamma rays from radium, but equal in intensity, under the same geometric conditions, to 7000gm of radium." This represented a significant achievement because the maximum activity of radium ever used in a "radium bomb" was 50 grams, given that the price of radium at that time was 100,000 pounds per gram. [48]

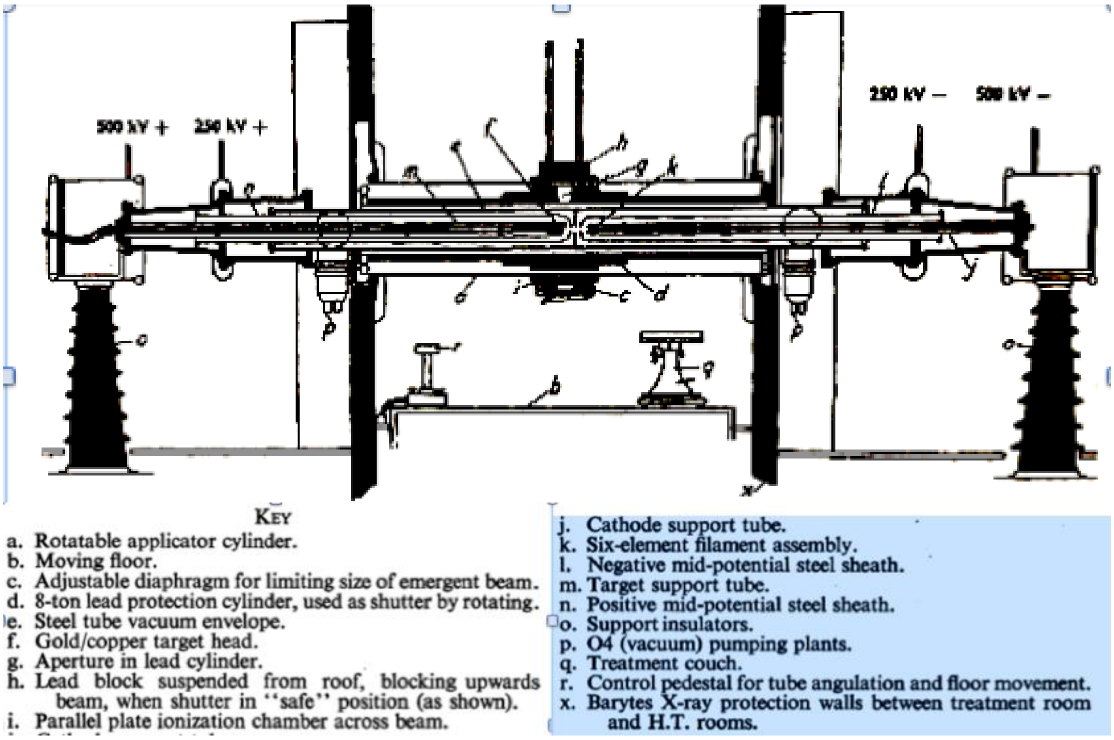


Fig 25 Details of tube (Barts Health NHS Trust Archives)

*A (4). Room protection*

The part of the building to contain the x ray tube would have to be specially provided with the appropriate radiation protection. See Fig. 26.

Figure 26. Photo of treatment room showing interlocking barytes bricks used for protection. (Barts Health NHS Trust Archives)

The walls were built with 125 tons of interlocking barytes bricks "preventing the egress of x rays that it is possible to store films within a few feet of the treatment room". The walls of the Great Hall were found to be 3 ft thick. The surrounding areas were limited to half tolerance dose, or approximately 0.5 R per week. For comparison, the present-day dose limit for radiation workers in the UK is 2 R (20 mSv) per year, and for members of the public 0.1 R (1 mSv) per year.

Protection around the tube was extremely important: the power was left on all day, so staff were receiving "leakage" radiation all the time they were in the treatment room.

6 inches of lead was in the direct beam (pointing upwards when staff were in the room, see letter "h" on tube diagram [25]). George Innes states that at 1 MV and 4.5 mA the x-ray leakage into the room was only "one half of tolerance dose" (0.5 R per week). The radiographers were limited to only spend 1 hour a day in the room. They wore "film badges" (dental films) to check the dose they received. [44]

In the treatment room the air conditioning plant provided 10 air changes per hour, and in the generator rooms 5 air changes per hour.

*A (5). Control Room*

The patient was viewed using a clever arrangement of curved mirrors. The radiographer side of these can be seen in the control room photograph. (See Fig 27.)

Fig 27. Photograph of control room showing dose rate meter; microphone for communication with patient; simple circuit with lights to show any faults; a periscope system of mirrors to view the patient on the other side of the barrier. (Barts Health NHS Trust Archives)

Providing the treatment room doors were closed (and interlocked) the whole of the lead cylinder blocking the beam could be made to rotate from the control desk. Automatic interlocks stopped the rotation when the x-ray aperture was aligned to the diaphragm on the outer sheath.

*A (6). Dose Control*

Just behind the diaphragm was mounted a 3-plate ionization chamber giving a signal through an amplifier to the meters on the control panel to indicate both dose rate and delivered dose.

As with modern x-ray tubes, the Sassoon tube needed to be kept evacuated. This was handled with oil diffusion pumps which were similar to pumps used in a 4 MV Linac installed at Newcastle in 1954 (see below). The oil diffusion pumps needed to remain vertical and so were supplemented with rotary backing pumps.

*A (7). Aids to improve treatment accuracy*

(1) X ray photography: Transmission radiography was used 50 years before it became routine in modern megavoltage therapy. George Innes noted that "The films were slightly improved if 2 mm of lead is placed between the patient and the film." [44] It wasn't until the 1970s that cassettes used for megavoltage verification films used a copper filter (an optimum material to use) for similar "need for build-up" reasons.

(2) A light beam indicating the position and size of the x-ray beam was used (see Newcastle linac below).

(3) A mechanical front-pointer also was used to aid in positioning the patient (see fig 26).

*B. Medical and other notes regarding the 1 MV unit at St. Bartholomew's (Barts) Hospital [48, 49,50]*

After many modifications the tube was put into operation in 1939 and operated at 1 MV and 4-5mA.

The unit operated day and night until 1965 for a total of 95,000 hours of operation. The longest period of breakdown was only a single afternoon (an extraordinary record in comparison to modern linac performance.) It continued to treat patients even after other high energy equipment was put into use including cobalt 60 units and linacs.

Statements made at the time by N S Finzi included

"I should consider the million-volt more accurate, and…one could get results with far less damage to normal tissues…and with less disturbance of the patient's general health." "…still higher voltages should be tried…" "We should aim at a machine which could work at first from 3 to 5 million volts, but which could be subsequently put up to 20 million volts."

Comments made by R Philips in his book included: "…it is unwise to make any rigid statements at this time…but it is clear that this million-volt x-ray installation has justified the wisdom of those who have contributed to the development of radiotherapy at St Bartholomew's Hospital over the last 25 years… and that supervoltage is superior to deep therapy in the treatment of certain types of malignant disease and they lend support to the view that a further increase in voltage to the 5 million volt range is likely to give still better clinical results." [50]

*C. Summary of the Physical Treatment Advantages of 1,000 kV X rays [48,49].*

Due to the increased depth doses, other physical factors and reduction in the skin reaction, the following advantages are obtained:

(1) Fewer fields can be used to deliver the lesion dose required and hence we obtain a simplification of the treatment plan with a resulting gain in accuracy.

(2) Alternatively, it is possible to reduce the dose level to some or all of the multiple fields.

(3) It is possible either to reduce the dose on fields passing through easily upset organs or alternatively in some cases to avoid irradiating them altogether, attaining the necessary

tumour dose by a less efficient routing of the beams to the lesion.

(4) In nearly all cases, 6,000 r can be delivered to the lesion in five weeks, no matter how deeply seated it is or how large the patient.

(5) By careful planning the dosage level can be made to fall off rapidly outside the volume to be irradiated, reducing the ill-effects on the patient.

(6) It will be noticed that no attempt is made to avoid beams passing through bony structures, since bone absorption at a million volts is very little greater than tissue, with the result that the isodose plans are a very near approach to the actual dose distribution in the patient, irrespective of whether bone is present or not. Also round the bone there is only a negligibly small trace of ionization in excess of that indicated by the r dosage level of the isodose.

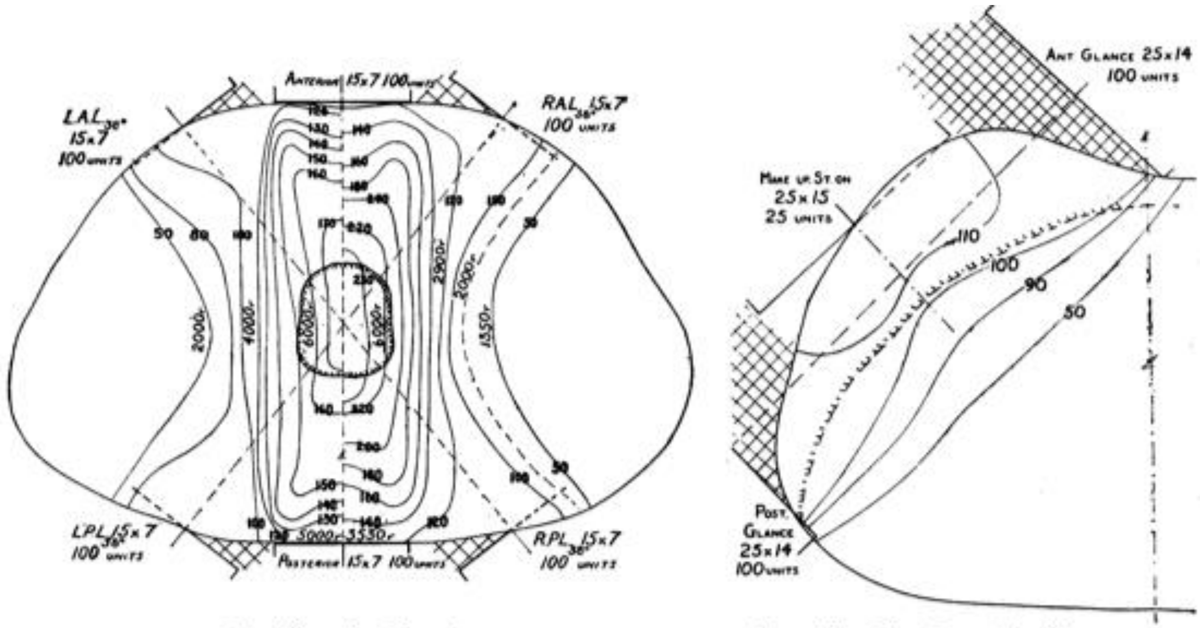


**FIG. 10.—Ca. Œsophagus.**
**Left: Treated by 250 kV, 1·5 mm. Cu H.V.L., 50 cm. F.S.D.**
**6,000 r $D_T \equiv$ 4,000 r/field $\equiv$ 5,000 r $D_S$.**
**Right: Treated by $10^6$ V, 9·3 mm. Cu H.V.L., 100 cm. F.S.D.**
**6,000 r $D_T \equiv$ 2,760 r/field $\equiv$ 3,530 r $D_S$.**
**(Maximum possible = 7,600 r $D_T$.)**

**FIG. 11.—Ca. Breast L. (Transverse section). Treated by $10^6$ V, 9·3 mm. Cu H.V.L., 100 cm. F.S.D.**

Fig. 28. Illustrations comparing treatments with 250 kV and 1 MV. Shown with the original figure captions. [50]

*D Concluding remarks regarding the 1 MV unit*

Ralph Philips (Fig. 29) became chief assistant at Barts in 1932, working under Dr NS Finzi who had pioneered treatments with supervoltage therapy. The book by Philips and other works were widely acclaimed in UK and USA. As early as 1938 Philips produced a complete regression in an inoperable rectal carcinoma. [50]

"I have had the privilege of using this apparatus at St Bartholomew's for nearly 2 years, during which time over 1500 individual treatments have been given…I should like to emphasize its absolute dependability-during this 2-year period. I have only twice been prevented from giving treatment as planned. A given set of conditions can be maintained absolutely constantly …and there is never any doubt as to the amount of radiation which is being administered.

"A further point is the simplicity of the apparatus; it is quite foolproof…The increasing use of technical apparatus and instruments of precision in medicine might lead one to think that medicine is a matter of pushing the right button or turning on the right tap, but I would emphasize that this is not the case. Radiotherapy, in spite of using these very precise instruments, has not become a mechanical science; it remains a part of the art of medicine, and each patient is an individual to be treated primarily from clinical knowledge, which is based on experience and observation. The installation of the 1. 000. 000-volt X-ray tube at St. Bartholomew's Hospital may well mark an important step forward in the campaign against cancer."

*Also, at this discussion both Dr WV Mayneord and Dr NS Finzi commented on the safe and reliable nature of this 1MV unit compared with those they had seen in the USA.*

Fig 29 Dr Ralph Philips with a patient on the 1MV x-ray set. Note the mechanical front pointer to indicate the focal-skin distance. (Barts Health NHS Trust Archives)

## VII. HIGH ENERGIES AFTER 1950 (COBALT 60 AND LINEAR ACCELERATORS)

It was noteworthy that the 1 MV unit continued to function so well, treating many patients until the 1960s. During the 1940s-1950s efforts were made to find: a) alternatives to the radium bombs (which could only be used at short distances because of the limited amount of radium available (usually only 3-5 grams, or Curies); and b) alternative means of accelerating electrons instead of direct high voltages.

### *A. Cobalt 60*

On 1 January 1947, the super-secret US Army Manhattan District had become the civilian-controlled Atomic Energy Commission (AEC) which then controlled the Oak Ridge reactor. The AEC made isotopes for the public and simultaneously, and secretly, made bombs. The AEC in 1947 authorized three hospitals for research in the use of radioisotopes in treating cancer. [51] In addition to ORINS (Oak Ridge Institute of Nuclear Strategies) in Knoxville, Tennessee, radioisotope research hospitals were approved in 1947 for Brookhaven, NY, and Argonne in Chicago. Dr. RL Clark and Dr M Brucer (members of the medical board of ORINS) arranged for a dialogue to begin between Dr. Brucer and LG Grimmett from the UK in the summer of 1949. [52] By August of 1949, Grimmett had a tentative telecobalt design which he presented to Brucer at ORINS. [53] By September 1949, Drs. Clark and Brucer were proposing collaboration on telecobalt. [54].

Thirty-three Physicians and physicists met together on 13$^{th}$ Feb 1950, and in July 1950 Dr Fletcher, who was the chief radiotherapist at MD Anderson from 1948 to 1981 and author of “A Textbook of Radiotherapy” [55]) presented a paper in Paris at the 5$^{th}$ International Cancer Congress advocating the use of Cobalt 60 for teletherapy.

However, it was Harold Johns who got ahead of the game. He had heard Mayneord talking at the Toronto General Hospital in 1946 where he enthusiastically acknowledged cobalt 60 as a replacement for radium. [52, 57] By August 1951 a cobalt unit had been built, and a source was installed in the Johns machine in Saskatoon (Fig. 30). Treatment began on 8th November. Johns reported a dose rate of 33 R/min at 80 cm. Johns also gained fame for his collimator. [56, 57]

Fig 30 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)

Another unit was delivered to London, Ontario for immediate clinical use on 27$^{th}$ October 1951.

In the UK the first cobalt 60 unit (the first in Europe) was installed at Mount Vernon Hospital in 1953 (presented by the BECC to MVH as a present to the country from a Canadian (Mr. J W McConnell).

Around the same time, a cobalt source was delivered to the MD Anderson Cancer Institute (as it was known at the time). This was described by Grimmett who, with Gilbert Fletcher, introduced it into clinical use. [54].

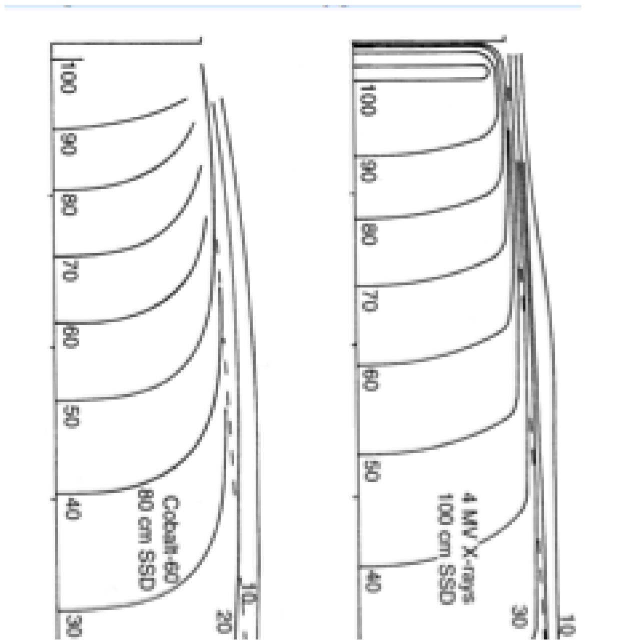


Fig. 31 Cobalt 60 isodose curves compared with 4MV (Newcastle linac 1953)

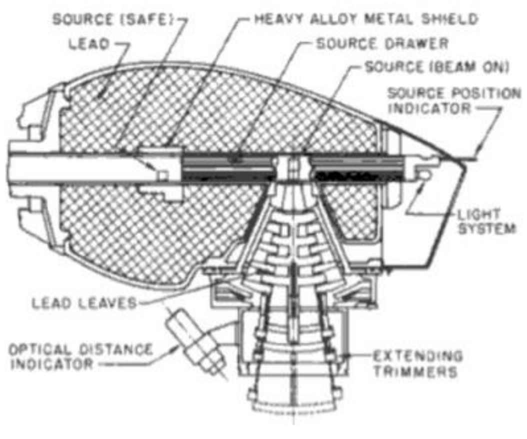


Fig 32 Cross section of the head of the Johns cobalt 60 unit (AECL)

*B Higher energy with x rays. The Van de Graaff Generator.*

A Van de Graaff generator for x-ray therapy was first designed and developed by Prof. J G Trump at MIT and built by the High Voltage Engineering Corporation of Cambridge (Massachusetts). This therapy apparatus was first installed in the UK at the Royal Cancer Hospital in London. Seven articles about this equipment appeared in BJR Vol 26 (1953) [58], see below:

*British Journal of Radiology, February 1953. Articles describing the first 2 MV Van de Graaff at the Royal Cancer Hospital.*

*I. Introduction: General Considerations. D W Smithers.*

*II. Beam Definition, Beam Direction, and Protection Problems. B M Wheatley and others.*

*III. Engineering of the Rotating Floor. J H King and others.*

*VI. Dose Distribution for Single Fields. B M Wheatley.*

*V. Three-Dimensional Dose Distribution with Rotation Techniques. P R Steed.*

*VI. Operation and Maintenance. I R Jones*

*VII. The First Two Years of Clinical Experiences with 2 MeV Radiotherapy. D W Smithers.*

This particular model allowed for rotation in two configurations: a) patient lying on the bed; b) patient sitting upright. The depth dose was very similar to cobalt 60; but, of course, dependent on FSD.

In the UK Van de Graaff generators were also installed in Sheffield and The Westminster Hospital London. [59] [60]

*C. Development of Linear Accelerators*

One of the first linear accelerators to be used clinically in the UK was installed at Newcastle-upon-Tyne in 1953. [62] It was the first to be isocentrically mounted (see below). [63] It used a long, 10-cm diameter waveguide, microwaves of 3000 MHz frequency, and a travelling waveguide with a feedback loop. The vacuum system consisted of an oil diffusion pump with a “backing rotary” pump.

The gantry (see figure) was mounted on large bearings 13.5 feet apart, counterbalanced at each bearing and driven by a variable speed motor controlled from the pedestal seen in the figure. The treatment room floor was stepped downwards behind the machine to a depth of 3 feet allowing the beam to be directed upwards at an angle of 30 degrees for posterior-oblique breast or chest tangential beams, so that the range of gantry movement was 210 degrees.

*C (1) Isocentric Mounting of gantry and couch.*

The gantry rotated about a point in space that was also the centre of rotation of the floor mounting of the couch and represented one of the first uses of an isocentrically-mounted couch. This hugely simplified the patient set-up. If the treatment target (the centre of the tumour) was set at the isocentre the gantry could be rotated to any angle chosen on the treatment plan and the beams would all pass through the target. The isocentre was defined by Howard Flanders as the point in space where the centres of rotation of the gantry, treatment head, and couch intersected. [63])

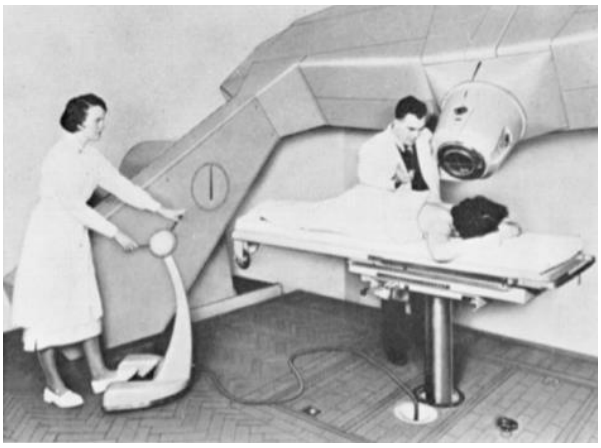

Fig 33. 4 MV linear accelerator at Newcastle-upon Tyne

*C (2) X-ray head.*

Surrounding the target there was enough lead to attenuate the unwanted x rays that emerged towards the walls and ceiling of the room (this ensured that less concrete and other building materials were required in the walls (particularly the secondary barriers) of the room. The primary collimator was made with tungsten or tungsten alloy; this reduced the x-ray dose rate in unwanted directions by at least 1/1000. The diaphragms were made with 4-inch (10 cm) lead blocks on pivots.

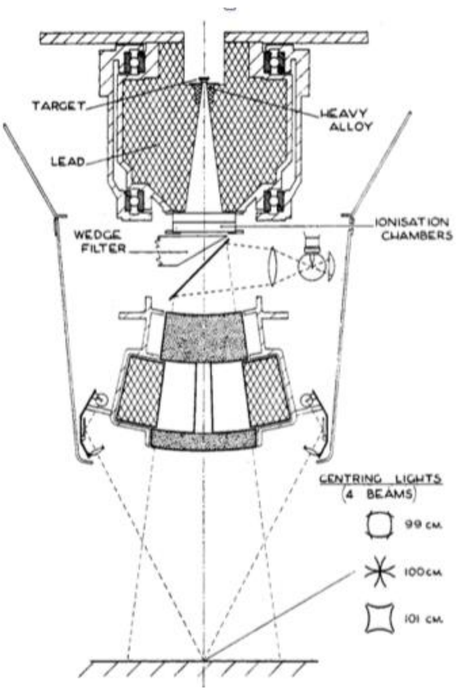


Fig 34. The beam defining system on the 4 MV Mullard linear accelerator (Newcastle) showing the optical system for field illumination and the range finder lights for centering and FSD indication.

*C (3) Optical System*

(1) Lamp and mirror to show the field size on patient's skin.

(2) Range-finder lights to determine the focal–skin distance of100 cm (nicknamed "Dam-buster lights" as a similar system was used in "Operation Chastise" during WW II to establish the critical 60-ft altitude of a bomber. See Wikipedia: (https://en.wikipedia.org/wiki/Operation_Chastise, accessed 26 July 2026.)

*C (4) Beam Characteristics*

The percent depth dose at 10 cm depth for a 10x10 cm field was about 63%. The build-up depth was 10 mm. This can be compared with modern linacs: 6 MV % DD=67%, build-up depth=15mm; 8 MV % DD=73%, build-up depth=20 mm.)

*C (5) Lifetime of the 4 MV accelerator at Newcastle*

In a letter to the editor from Bill Ross and Michael Day, they described the lifetime of the Newcastle accelerator as lasting from the first patient treatment on Dec 3, 1953, to the last patient treatment on May 22, 1981. During that time, the unit delivered 18,272 courses of treatment and more than 600,000 fields. [64]

Fig 35. Control desk for 4MV linac with dose and dose rate meters; and periscope for patient viewing. Frank Farmer procured a cast-off submarine periscope for the Newcastle 4MV linear accelerator at Newcastle.

Further details of the development of linear accelerators can be read in the articles by: DI Thwaites and JB Touhy [61] and MD Schulz [38].

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