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Design Requirements for Megavoltage X-Ray Machines for Cancer Treatment in Developing Countries

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Report of an Advisory Group Consultation
Washington, D.C.
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To Craig Nunan (1918-1994)
who could have developed
"the" machine.

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PREFACE

One of the primary concerns of the Pan American Health Organization (PAHO)/ Regional Office for the Americas of the World Health Organization (WHO), is the equity of health services. In cancer treatment inequities presently exist as a result of the high costs involved in the establishment, staffing, and operation of surgery, chemotherapy, and radiotherapy services. In developing countries surgery is limited in its role as a result of the advanced stage of the diseases when it is usually encountered, and chemotherapy is expensive. Radiotherapy remains the most important therapeutic approach for most tumors, for both cure and palliation. One of the main limitations to making radiotherapy readily available in developing countries is the expense involved in the purchase and maintenance of appropriate equipment.

Often radiotherapy is performed with antiquated cobalt-60 (^{60}Co) units, the radioactive sources of which have long since decayed, and, thus, the treatments are ineffective. Furthermore, the cost involved in the disposal of spent radionuclide sources discourages owners from their proper removal and storage, and accidents occur. Although microwave electron linear accelerators of present design provide excellent beam characteristics, many developing countries do not have the infrastructure to maintain such machines.

PAHO, in collaboration with the WHO Headquarters Office, the International Atomic Energy Agency (IAEA), and the United Nations Industrial Development Organization (UNIDO) organized an Advisory Group consultation on the Design Requirements for Megavoltage X-Ray Machines for Cancer Treatment in Developing Countries. This consultation was held in Washington, D.C., to explore the possibilities of designing a more elementary electrical teletherapy machine which would have low capital and operating costs while taking advantage of the latest advances in technology.

The resulting analysis and recommendations of the Advisory Group Consultation are summarized in this report, which was prepared by the participants and is published by the Los Alamos National Laboratory on behalf of the sponsoring organizations.

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EXECUTIVE SUMMARY

An Advisory Group Consultation on the Design Requirements for Megavoltage X-Ray Machines for Cancer Treatment in Developing Countries was organized by PAHO in Washington, D.C., 6-10 December 1993, with the collaboration of WHO Headquarters, the IAEA, and UNIDO. It was attended by 40 participants including radiation oncologists, physicists, technologists, and representatives from radiotherapy equipment manufacturers. The goal of this Consultation was to propose design alternatives for megavoltage x-ray units that have the potential of lower manufacturing cost, simpler design, and less frequent and costly maintenance than current electron accelerators.

As the populations age, the availability of equipment, facilities, and staff for cancer treatment is emerging as a major problem in developing countries since they have only a very small percentage of the world's cancer therapy resources. According to estimates by WHO there are currently 9 million new cancer cases per year worldwide. This number is expected to increase to about 15 million new cases by the year 2015, with about two-thirds of these cases occurring in developing countries. It is likely that radiotherapy will, for years to come, remain one of the most important treatment modalities, for both cure and palliation.

The dimensions and radiation characteristics of high-energy x-ray machines required to meet the needs of developing countries were defined and found to be very similar to those of high-quality low-megavoltage machines presently used in the developed countries. The Consultation concurred that such a machine would be equally suited for use in both developing and developed countries.

Major performance characteristics agreed upon

Two-thirds of patients in developing countries are treated with simple parallel-opposed fields. It is desirable to avoid the more complex treatment planning required when using more than two fields. Therefore, the photon beam energy should be selected to limit hot spots and the consequent risk of fibrosis at the depth of maximum dose in thick patient sections when using parallel-opposed fields. The dose buildup should provide an adequate dose at 5 mm depth for superficial lymph node irradiation, while minimizing the skin dose to avoid telangiectasia. The beam quality should therefore be selected so that for a 25 cm thick patient the maximum dose in a 10 x 10 cm field will be less than 115% (preferably less than 110%) of the dose delivered to a central tumor in an equally weighted parallel-opposed beam configuration. In addition the superficial 90% isodose should occur at a depth of less than 5 mm. In practice this implies that the photon beam should provide deeper penetration than a ^{60}Co beam. In general a photon beam in the 5-6 MV range or a highly filtered 4 MV beam with low electron contamination is needed to meet these requirements. There was a strong feeling that if the machine is to be an accelerator, it must provide significantly greater beam penetration than ^{60}Co.

The proposed x-ray machine should have the following dimensions:

1. Low isocenter height. No higher than 130 cm, with 115 cm preferred. A small depression in the couch turntable is permissible but generally not desirable for safety reasons.
2. A 100 cm source-to-axis distance (SAD) is preferred; a SAD of 80 cm is acceptable if adequate field sizes and patient clearance in isocentric treatments are provided. An isocentric clearance of at least 35 cm from the front flange of the collimator head is required when accessories are attached.
3. The vertical travel of the couch should be at least 65 cm below isocenter. The couch rotation should be at least 90 degrees from the isocentric axis. The field size at isocenter should be at least 30 cm x 30 cm (at least 42 cm x 42 cm on the surface of a 25 cm thick patient with the couch fully lowered).

The following accelerator technologies were considered as Category A - meriting further exploration or Category B - probably usable to reach the goal

A-1. Low-energy linac, in-line accelerator design.
A-2. Low-energy linac, bent beam design.
A-3. Integrated pulsed klystron and low-energy linac combined in same vacuum envelope.
A-4. Low-energy microtron mounted in line with the radiation head.
A-5. Low-energy accelerator built of replaceable, standardized modules for ease of maintenance.
A-6. Miniaturization via shorter microwave wavelength (e.g., 3 cm instead of present 10 cm) with possible improvement of magnetron reliability.
A-7. Replacing the high-voltage modulator with a pulsed magnetron magnet.
B-1. Low-energy betatron mounted in the radiation head, with its magnet driven at about 10 kHz to achieve adequate x-ray intensity at 6 MV.
B-2. Low-energy rhodotron, a continuous-wave (cw) electron accelerator using a half-wave coaxial cavity to accelerate the beam on multiple passes.
B-3. cw microwave accelerator (no modulator, simple magnetron) with reflected beam to increase accelerating potential to 4 or 6 MV.
B-4. A 2 or 2.5 MV direct current (dc) accelerator with power supplies cascaded, transformer-coupled, nested, or of an electrostatic type (i.e., Laddertron or Pelletron). X-ray beam filtered to 3 MV penetration.
B-5. ^{60}Co unit with a 100 cm SAD at 1.6–1.8 Gy/min (~3 MV equivalent penetration).

The following descriptions summarize some of these systems

1. ***Electron Linear Accelerators (Linac).*** There are approximately 2,500 linacs operating in the U.S. and perhaps double that number worldwide. Linacs are the most widely used device for the production of x-rays in the range of 4-20 MV. However, their complexity results in frequent breakdowns that can cause unacceptably long delays in patient treatments. In the U.S. these machines cost between $500,000 and $1.2 million excluding installation. To be a serious contender for developing countries, linacs would have to be simplified to reduce their cost, and their reliability would have to be markedly improved.

2. ***Cobalt-60.*** The ^{60}Co radioactive source, having a 5.3 year half-life, provides a level of reliability not yet achieved by electrically powered devices. However, mechanical problems do arise that can pose serious radiation exposure risks for both the patient and medical staff because the radiation source cannot be turned "off." Because of their relatively simple mechanical construction and few electrical components, the cost of ^{60}Co units is typically less than that of electron accelerators. The main problems with ^{60}Co units are their relatively low dose rates, which reduce patient throughput, a steadily decreasing dose rate over time, which dictates that the source be changed every 3-4 years, dose distributions in the patient that are inferior to those provided by high-energy x-ray machines, and disposal of spent sources which, in the past, has created public health problems in developing countries.

3. ***Microtron.*** There are about 40 commercially produced microtrons operating worldwide. Microtrons are inherently simpler than linacs and, with a comparable level of development, might achieve greater reliability. The production of 4-8 MV x-rays is easily achieved in a microtron 30-50 cm in diameter (depending on the injection method), which can be mounted at the treatment head of a rotating gantry.

4. ***Direct-coupled-klystron linac.*** This device, under development at Los Alamos National Laboratory, is similar to the standard linac in the way it accelerates electrons. However, it

differs in that the klystron that is directly coupled to the accelerator is used as an radio-frequency (rf) oscillator as well as an rf amplifier. Some of the most fault-prone components of the standard linac are eliminated, simplifying both the electronic and mechanical aspects of the x-ray system.

5. ***Modular-rf-supply linac.*** In this proposed linac design, the rf power supply (magnetron- or klystron-based) and the accelerator would be constructed as an integral unit, which would be replaced in its entirety should any component fail. To increase the lifetime of the magnetrons, their magnets would be pulsed by a dc supply, thereby eliminating thyratrons which have a high failure rate.

6. ***High-frequency linac.*** The operating frequency of a standard linac is 3 GHz. Frequencies higher than 10 GHz are being investigated. Such an increase in operating frequency would result in a more compact machine with a reduction in both weight and cost.

7. ***High-frequency betatron.*** The first betatrons were operating in the 1940s with electron beam energies of 20-50 MeV at frequencies of 60-180 Hz. A betatron operating at 10 kHz could produce 6 MV x-ray beams having clinically acceptable dose rates. The main advantage of the betatron is its high degree of reliability that derives from its simple, low-frequency electronic components.

8. ***Rhodotron.*** Designed in France for food sterilization, this nonlinear electron accelerator utilizes a cw, 300 MHz rf source. This lower frequency permits the use of reliable vacuum tubes, and its cw operation eliminates the need for a high-voltage pulse modulator, hopefully improving its reliability compared with the standard linac.

9. ***dc Accelerators.*** In both clinical and research laboratories, these machines have proven to be highly reliable and, because of advances in technology, can now be mounted in a compact gantry. However, the 2-3 MeV maximum energy achievable was considered too low by most users. Heavy filtration would allow beam characteristics similar to a conventional 3 or 4 MeV accelerator. With heavy filtration low beam currents may continue to be a problem.

Additional aspects considered and recommendations made

Many interruptions in the use of modern medical electron accelerators are caused by failures of relatively simple electrical, hydraulic, or mechanical components. Difficulties in providing satisfactory maintenance are compounded by administrative problems and delays in addition to inadequate organization, infrastructure, and funding which often lie beyond the control of the individual radiotherapy facility. Some of the problems could be avoided at the equipment design stage by incorporating components of high reliability that are already available for industrial use, and by using a modular design with easily replaceable components. It would be of additional benefit if the modules were compatible in machines from different manufacturers.

Suggestions were made for training programs and for a suitable organization to provide maintenance and to stock spare parts. It was recognized that the term "Developing Countries" has been applied to an economically very heterogeneous group of nations. In many of these nations the economy is now expanding so rapidly that the term "Developing Countries" has been changed to "Emerging Markets" by investors. In these nations, the funding situation for radiation therapy can be expected to improve markedly. This situation will affect the types and numbers of x-ray equipment that will be put into service over the next 25 years, as well as the staffing for their operation and maintenance. It is hoped that this change will spread to all developing countries.

The current manufacturers of electron linear accelerators and microtrons should be encouraged to design and prototype a super-reliable x-ray system operating in the 4-6 MV range and meeting the established performance specifications. This encouragement should come from the accelerator designers who might cooperate with the manufacturers as well as representatives of the developing nations who can best make the case for their needs.

INTRODUCTION

According to WHO estimates, there are currently approximately 9 million new cancer cases per year, worldwide. This number is expected to increase to about 15 million new cases by the year 2015, with about two-thirds of these cases occurring in developing countries.

Radiotherapy will, for years to come, be the most important therapy approach for most of these tumors, both for cure and palliation. Surgery is limited in its role as a result of the advanced stages of the diseases encountered in developing countries, and chemotherapy is expensive. An analysis of the situation regarding cancer treatment in developing countries has revealed equipment and personnel problems that have little chance of being solved if the current approach to providing therapy is not significantly improved. In particular, there is an urgent need for more radiotherapy equipment as well as for training programs for personnel to use and maintain the equipment effectively.

Most nonindustrialized countries perform radiation therapy primarily with ^{60}Co treatment machines. This has been and in many cases continues to be the technology of choice because these machines are relatively reliable and are simple to operate and repair. However, the radioactive source is often not replaced for economic reasons, leading to ineffective treatments. Also, these countries often do not have the infrastructure to ensure the safe disposal of the source.

It is estimated that in developing countries approximately 2,300 megavoltage teletherapy units are currently installed, primarily ^{60}Co units. In these countries, the typical incidence of new cancer patients is 75 to 150 per 100,000 population. To serve a current population of 4.4 billion, assuming 4.4 million new cancer cases per year, 50% of which requiring radiotherapy, and assuming one machine per 500 new cancer cases treated, the current need is for a total of 4,400 machines. By the year 2015, barring a dramatic and unforeseen cure for cancer, a total of 10,000 machines will be needed to provide treatment for an estimated 10 million new cancer cases per year in developing countries.

With this envisaged increase in demand for radiation therapy worldwide, especially in the developing countries, great attention should be given to providing reliable and safe equipment, and measures should be taken to improve the qualifications and continuing education of the operators.

Most radiation oncology departments in the U.S. and in Europe use mainly linear accelerators, which offer a variety of treatment modes and contain no radioisotopes. Some of these units are very expensive and difficult to maintain, and the infrastructure to use them properly is often lacking in developing areas. Thus, for the purpose of improving the availability of radiation therapy, manufacturers and major laboratories are being encouraged to consider the design and development of megavoltage x-ray machines that would be much simpler than present microwave electron linear accelerators. Hence, PAHO, WHO, IAEA, and UNIDO are cooperating to initiate a program to define the performance requirements and design alternatives for such a machine.

As the first step in this program, an Advisory Group Consultation on "Design Requirements for Megavoltage X-ray Machines for Cancer Treatment in Developing Countries" was organized by PAHO at its office, 525 23rd Street, NW, Washington, D.C., 6-10 December 1993, with the participation of WHO Headquarters, IAEA, and UNIDO. It was attended by 40 participants including radiation oncologists, physicists, technologists and representatives from radiotherapy equipment manufacturers. The list of attendees is included in Appendix 1.

The Consultation was welcomed with opening remarks by Dr. José María Paganini, Director of the Division of Health Systems and Services of PAHO, and introductory statements by representatives of the participating organizations; PAHO, WHO, IAEA, and UNIDO.

SESSION I: ANALYSIS OF THE SITUATION

Moderator: G. Hanson
Discussion Leader: J.M.V. Burgers

To provide an understanding of the situation for all the participants, especially those not familiar with radiation therapy, introductory presentations were made. The most important points mentioned with regard to the topic of the Consultation are summarized below.

Review of the Role of WHO in Basic Radiotherapy: G. Hanson

Dr. Hanson reviewed the recommendations that have been made by WHO and IAEA since the mid 1960s concerning equipment, quoting relevant observations and conclusions. These are contained in reports of various expert group meetings, for example WHO Technical Report Series Nos. 322, 328 (a joint WHO-IAEA meeting), and 644. The earlier recommendations have been reconfirmed in more recent meetings convened by IAEA and WHO. The need for a scientifically sound, robust, and reliable treatment unit capable of high-quality performance has been universally recognized. Up to the present time the consensus is that a ^{60}Co machine is preferable, and electron accelerators could not be universally recommended for use in developing countries.

Because of difficulties with the timely replacement of ^{60}Co sources, including the proper disposal of spent sources, and because of the difficulties encountered in providing the proper infrastructure to effectively utilize electron accelerators, the participating agencies (PAHO, WHO, IAEA, UNIDO) have organized this Advisory Group Consultation.

Epidemiology of Cancer in Developing Countries: K. Nair

Dr. Nair pointed out that cancer is an emerging problem in the less developed countries. With nearly two-thirds of the population in the world, they are currently suffering one-half the cancers. At present only 5.5% of the deaths are due to cancer in these countries, whereas in the developed countries, 20% of the deaths are due to cancer. The emergence of the cancer problem is due to the changing age structure of the populations in the lesser developed countries because of increased life expectancy, control of communicable diseases, and widespread use of tobacco. By 2015 it is expected that because of the influence of these factors, 75% of the cancer cases in the world will occur in the developing countries, which have just 5% of the resources for their management. The common cancers in developing countries are cervical, head and neck, and breast cancers, for all of which radiotherapy plays an important curative role.

A summary of the most frequent types of cancer recorded worldwide and the strategy for their management was presented as shown in Tables 1 and 2.

In the discussion, different cancer control measures were discussed, and, in particular, the importance of health education programs was emphasized.

Current and Future Role of Radiation Therapy of Cancer: J. M. V. Burgers

The relative role of surgery and radiotherapy and their combination for various sites was presented. For large tumors and advanced stages of disease, radiotherapy is more important and can be curative. In developing countries the pattern of cancer incidence is different from developed countries because of the younger age of the population and differences in lifestyle (Figure 1). Certain types of tumors are frequent and are accessible for radiotherapy, i.e., head and neck, cervix, breast and skin. To increase the therapeutic ratio, the radiotherapy dose should be as high and as homogeneous as possible, while normal tissue should be shielded whenever possible. These procedures require the use of beam-shaping devices, such as wedges and blocks, and isocentric movements to avoid overlap between divergent beams.

Table 1

Estimates of the Worldwide Incidence of Eighteen Major Cancers in 1985[1]

Males			Females			Both Sexes		
Site	Number	%	Site	Number	%	Site	Number	%
1. Lung	667	17.6	1. Breast	719	19.1	1. Lung	886	11.8
2. Stomach	473	12.3	2. Cervix uteri	437	11.6	2. Stomach	755	9.9
3. Colon/rectum	331	8.6	3. Colon/rectum	346	9.2	3. Breast	720	9.4
4. Prostate	291	7.6	4. Stomach	282	7.5	4. Colon/rectum	678	8.9
5. Mouth/pharynx	270	7.0	5. Lung	219	5.8	5. Cervix uteri	437	5.7
6. Liver	214	5.6	6. Ovary	162	4.3	6. Mouth/pharynx	412	5.4
7. Esophagus	196	5.1	7. Mouth/pharynx	143	3.8	7. Lymphoma	316	4.2
8. Bladder	181	4.7	8. Corpus uteri	140	3.7	8. Liver	315	4.1
9. Lymphoma	182	4.7	9. Lymphoma	135	3.6	9. Esophagus	304	4.0
10. Leukemia	121	3.1	10. Esophagus	108	2.9	10. Prostate	291	3.8
11. Larynx	121	3.1	11. Liver	101	2.7	11. Bladder	243	3.2
12. Pancreas	97	2.5	12. Leukemia	96	2.5	12. Leukemia	216	2.8

Table 2

Priorities and Strategies for Cancer Control in Developing Countries[2]

Tumor*	Primary Prevention	Early Diagnosis	Curative Therapy**	Pain Relief and Palliative Care
1. Lung	++	-	-	++
2. Stomach	+	-	-	++
3. Breast	+	++	++	++
4. Colon/rectum	+	-	-	++
5. Cervix	+	++	++	++
6. Mouth/pharynx	++	+	++	++
7. Esophagus	+	-	-	++
8. Liver	++	-	-	++

* Listed in the order of the eight most common tumors globally

** Curative for the majority of cases provided they are found early

++ effective, + partially effective, - noneffective

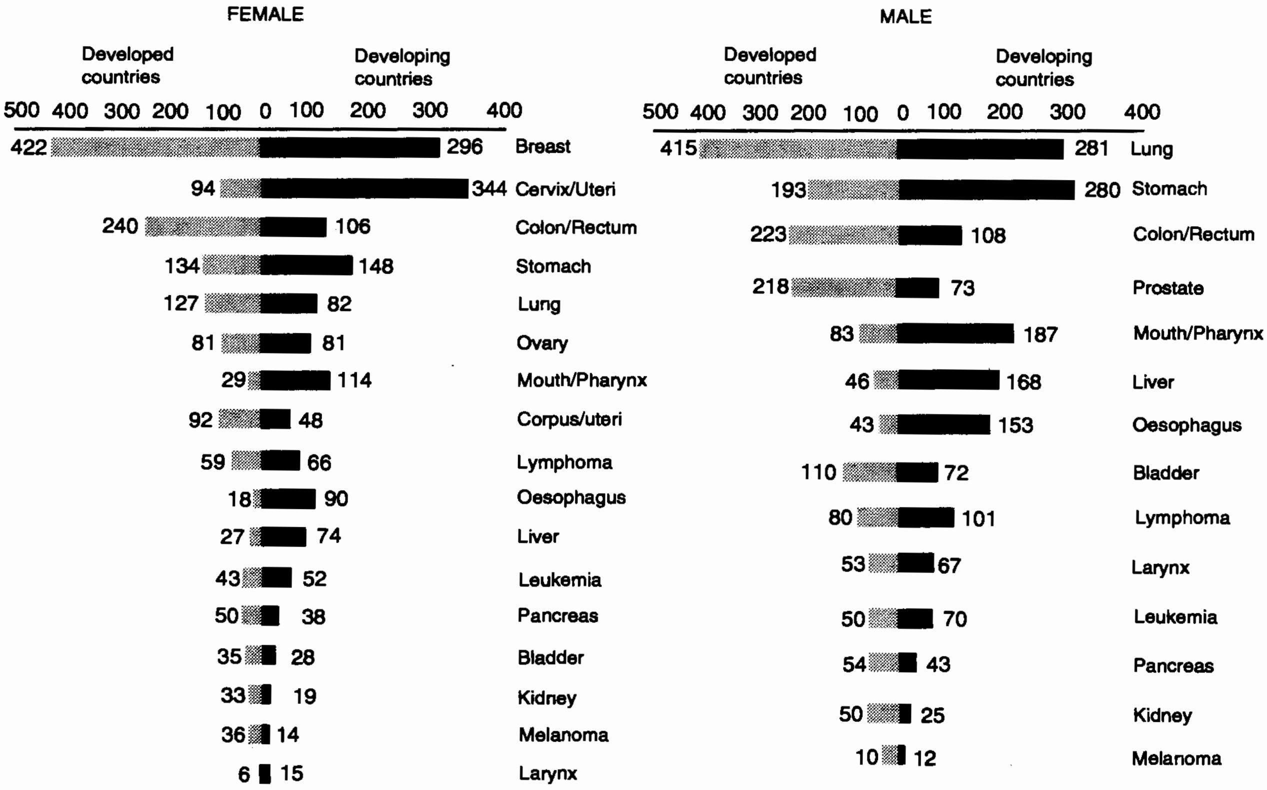

Figure 1. Estimated numbers of new cases (in thousands) of 17 cancers in women and 14 cancers in men in developed and developing areas of the world.[3]

Physical Aspects of Current Treatment Modalities: H. Svensson

The number of megavoltage machines available per 1 million of population was compared for 10 countries in the western world. It ranges from 8.2 in the U.S. to 3.4 in the U.K. with 70%-90% of the machines being electron accelerators. Penetration and skin-sparing depend on beam energy, but with sophisticated planning, a ^{60}Co or a low-energy electron accelerator can give satisfactory dose distributions without the need for higher energies. Penumbra (P80/20) is smallest with 4-6 MV beams, generally below 8 mm for most commercial units and increases slightly with energy. In the discussion it was mentioned that the penumbra width is sometimes less than the day-to-day variation in patient setup, as shown by repeated portal imaging.

Equipment, Personnel, and Operating Costs: V. Sahadevan

Considering the scarcity of material resources, the possibility of reducing the number of treatment sessions through the use of higher dose per fraction could be considered for some tumors. However, quality must not be sacrificed, and all patients must receive consistent high-quality treatments and associated medical care.

A current comparison of financial cost data for machines in the United States is presented in Table 3. During the discussion, K. Nair presented financial data from India that are reproduced in Table 4.

Table 3

Economics of Supervoltage Equipment for Radiation Therapy in an Industrialized Country

(V. Sahadevan)

	^{60}Co	6 MV Photons	6 MV Electrons	6 & 10 MV Electrons	
Physical Factors					
Radiation Output (R/min at 1 m)	*200	*250–300	200	200	300
Photon 10 cm Depth Dose (%)	58	67	67	67	75
10 cm Dose Rate (R/min)	116	134	134	134	225
Time Need for Setup (min)	15	15	15	15	15
Time to Reach 200 rads (min)	1.72	1.49	1.49	1.49	0.89
Total Duration of Treatment (min)	18	17	17	17	16
Treatments/yr. (249 treatment days)	6540	7030	7030	7030	7470
Capital Costs ($)					
Equipment	400,000	602,000	827,000	989,600	
Source	50,000	0	0	0	
Therapy Room	100,000	100,000	100,000	100,000	
Total Cost ($)	550,000	702,000	927,000	1,089,600	
Annual Costs ($)					
Amortization -- Int. & Prin.					
Equipment 10 Yr. @ 9%	59,612	89,716	123,247	147,480	
Building 20 Yr. @ 8%	10,185	10,185	10,185	10,185	
Source 5 Yr. @ 8%	12,523		0 0	0	
Maintenance ($)					
Parts and Service	4,000	30,000	35,000	40,000	
Total Annual Cost ($)	86,320	129,901	168,432	197,665	
Cost Per Treatment	13	19	24	27	
Comparative 1966 Annual Cost ($)	15,370	29,420	—	—	

* *These are maximum values. (Typical values may be 150 for ^{60}Co and 200 for the linac.)*

Maintenance Problems in South America: N. Urdaneta

Information on radiotherapy facilities and equipment used in representative countries of South America was presented including types of megavoltage machines (principally ^{60}Co and linear accelerators), orthovoltage units, computer based treatment-planning systems and simulators, as well as estimates of the number of out-of-service units and the number of those needing repair or replacement. The result for one country (Venezuela), in which a significant effort has been made to provide a maintenance and repair program, is summarized in Tables 5, 6, 7, 8 and 9.

Table 4

Comparison on Expenditure and Income
^{60}Co Unit vs. Linear Accelerator in a Developing Country (for 15 years)

(Adapted from K. Nair)

Particulars	^{60}Co Unit (Rupees)	Low-Energy Linear Accelerator (Rupees)	Proposed Linear Accelerator (Rupees)
Cost of Machine	8.0M	20.0M	12.0M
Source (150 R/min)+Loading +Transportation	1.7M	-	-
Building	0.7M	0.7M	0.7M
Source Changes (2 times)	3.5M	-	-
Servicing	0.4M	2.5M	2.0M
Spares	1.0M	2.5M	2.0M
Staff (one radiotherapist, one physicist and two radiographers)	2.7M	2.7M	2.7M
Electricity, etc.	0.1M	0.2M	0.2M
Total expenditure	18.1M	28.6M	19.6M
Income from Treating 500 Patients* per Year for 15 Years @ 1,200 Rupees per Patient	9.0M	9.0M	9.0M
Number of Patients Treated in 15 Years	7,500	7,500	7,500
Cost per Patient over 15-Year Machine Lifetime	2,413 ($69)	3,813 ($109)	2,613 ($75)
Total Cost Minus Total Income	1,213 ($35)	2,613 ($75)	1,413 ($40)

** While the comparison was done for the same number of patients being treated in both machines, it is acknowledged that when the linac works, it can treat a larger number of patients.*

Table 5

Radiation Therapy Facilities in Venezuela

(N. Urdaneta)

Space	Appropriate	Inappropriate	Non Existent
Waiting Room	13	5	
Clinic	14	3	1
Treatment Room	15	3	
Conference Room	8	4	6
Darkroom	6	4	8
Anesthesia	6	2	10
Treatment Planning	4	2	12

Table 6

Radiation Therapy Equipment and Treatment Planning Computers in Venezuela

(N. Urdaneta)

Type	No. of Units	Working	Not Working
Orthovoltage	7	4	3
^{60}Co	20	17	3
Linear Accelerators	7	5	2
Simulators	7	5	2
T.P. Computers	5	3	2

Table 7

Condition of the ^{60}Co Units in Venezuela

(N. Urdaneta)

Condition	Appropriate	Inappropriate
Working period (< 10 years)	7	13
Output (> 100 cGy/min)	5	15
SSD* (≥ 80 cm)	14	6
Field Size (≥ 25 cm)	18	2
Rotation Capability	14	6
Treatment Couch	17	3
Maintenance	14	6
Calibration (< 1 year)	17	3

(*source-to-skin distance)

Table 8

Condition of the Linear Accelerators in Venezuela

(N. Urdaneta)

Condition	Appropriate	Inappropriate
Working Period (< 10 years)	3	4
Treatment Couch	6	1
Maintenance	6	1
Calibration (< 1 year)	6	1

Table 9

Maintenance Cost per Year
^{60}Co vs. Clinac 4 in Venezuela
(N. Urdaneta)

Activity	^{60}Co	Clinac-4
Preventive Maintenance and Inspection	$ 2,000	$ 4,000
Source Replacement	$ 10,000	-
Part Replacement	-	$ 14,000
Total Cost	$ 12,000	$ 18,000

The following observations were made on behalf of Dr. A. Luongo, a radiotherapist from Uruguay:

1. In some countries the existing radiotherapy equipment is functioning in suboptimal condition not because of technical design aspects (for example, there are many machines capable of operating at SADs of at least 80 cm), but because it is old and in need of replacement.
2. In other countries older equipment actually constitutes an unacceptable risk and must be removed from service.
3. The situation of orthovoltage units is much worse than that of megavoltage equipment, with only a small number of these units operational in some countries.

Underlying reasons for the unsatisfactory maintenance and radiation therapy include

(a) lack of a health policy
(b) political and economic instability
(c) lack of regulatory controls and standards
(d) lack of resources
(e) insufficient training
(f) lack of specialization
(g) insufficiently distributed infrastructure
(h) bureaucracy

Dr. Urdaneta presented a histogram prepared by Dr. Borrás (Figure 2) that shows the 1992 distribution of absorbed dose rate at 5 cm depth for ^{60}Co units in Latin America and the Caribbean excluding those in Argentina, Brazil and Mexico. The data were derived from the annual IAEA/WHO postal dosimetry intercomparison of high-energy radiotherapy units. The histogram shows that more than 50% of the units tested would require treatment times of over 4 min to deliver 2 Gy to the tumor. To compensate for the low absorbed dose rate at the treatment distance and still treat a very large number of patients, it has become a common practice in these countries to shorten the treatment distance, often without correcting the percentage depth dose tables in clinical use, and to deliver lower doses than necessary. In no case are exposure times increased to compensate for the low dose rates. The consequences of such malpractice are not only that inaccurate doses are being delivered (the 1992 intercomparison showed errors of more than 38%!), but that treatments are ineffective, erroneously fostering the idea that cancer is incurable. Thus the health authorities of Latin America and Caribbean countries do not assign proper budgets to radiotherapy services.

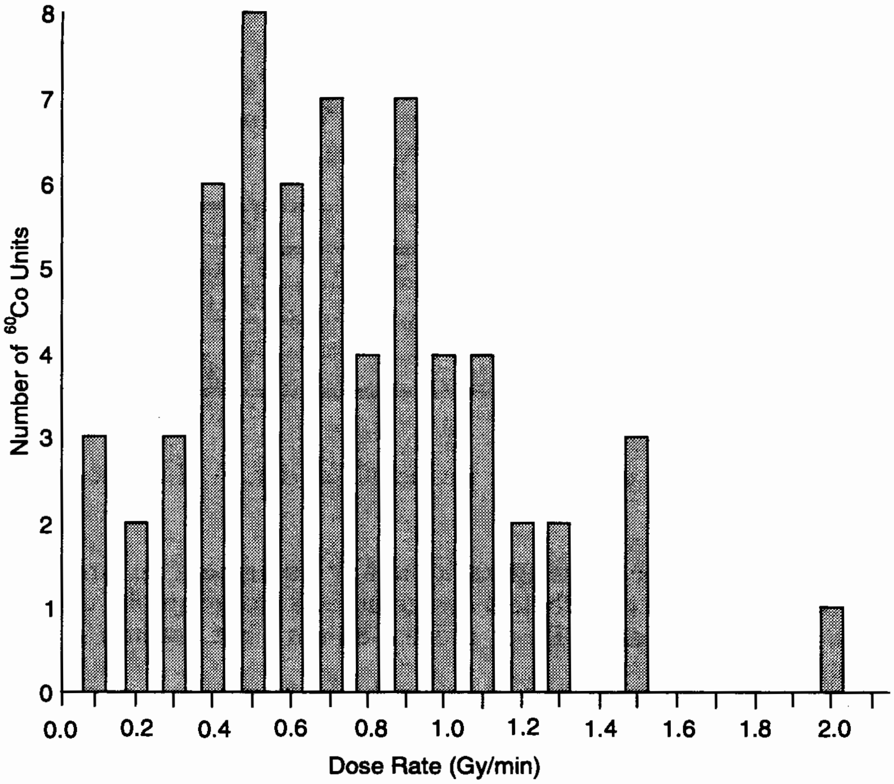

Figure 2. Absorbed Dose Rate at 5 cm Depth for 62 Latin American and Caribbean ^{60}Co Units (Excluding Argentina, Brazil and Mexico) in 1992

A separate problem is the proper disposal of the used sources. The costs involved are sometimes as great as those for purchasing a new source. In several instances it was found that the teletherapy head had been buried on the hospital grounds without any previous conditioning. To prevent accidents like the ones in Ciudad Juarez, Mexico, and Goiania, Brazil, PAHO has recently been involved in two recovery operations in two countries. In one case, a source had been buried in a municipal garbage dump. In another case three sources had been stored in an abandoned clinic.

Maintenance Problems in Africa: Otim-Oyet

In Sub-Saharan Africa, excluding South Africa, the source of maintenance problems is deeply rooted in the overall lack of human and material resources. It is estimated that for a population of 285 million with approximately 430,000 new cancer cases per year, there are only 25 to 30 radiation oncologists and only about 50 oncologists of other specialties. The supporting staff (medical physicists, radiological technologists, electronic technicians, and engineers) are likewise extremely scarce.

Thus the main problems are

(a) little awareness of the role of radiotherapy
(b) a lack of knowledge of cancer-management possibilities
(c) limited financial support for radiotherapy facilities
(d) few trained radiation oncologists, physicists, and engineers

Maintenance Problems in Eastern Europe: S.P. Kapitza

The general principle of the microtron, a compact, cyclic electron accelerator, was described. It is a relatively simple machine with circular beam orbits, using radiofrequency components that are standard for radar stations. The first model for radiation therapy was produced in 1985, and to date six of these machines have been installed in Eastern Europe. These units have had the following service experience.

(a) The rf cavities are cleaned every 6 months, and none of the original accelerating cavities have been replaced to date.
(b) One lanthanum hexaboride emitter was replaced.
(c) Three spiral cathode heater filaments have been replaced.
(d) The standard Russian magnetrons were replaced quarterly.
(e) The anode/cathode units of the ion pump were replaced annually.

Maintenance Problems in Asia: U. Madhvanath

Maintenance problems are directly linked to the time invested in machine servicing and to the availability of spare parts and trained manpower. Unfortunately, the very meager facilities that exist for the large Asian population do not allow any time whatsoever to carry out preventive maintenance or quality assurance programs. The present situation in some Asian countries was reviewed.

Radiotherapy facilities: For the treatment of cancer with radiation, as a rule of thumb, at least one ^{60}Co unit is required per million inhabitants in Asia, where the average life expectancy is about 55 years. Dr. Madhvanath suggested that in the developed countries of Asia there are between 4 and 8 units (^{60}Co or accelerator) per million inhabitants. In contrast, Nepal has one ^{60}Co unit for 20 million, Bangladesh has one unit for 110 million, and Myanmar has 6 units for 38 million. The two most populous countries, Peoples Republic of China (with a population of 1050 million) and India (845 million) have 350 and 180 teletherapy units respectively, corresponding to 30% and 20% of the required number of units. The facilities in Thailand, Indonesia, and the Gulf countries are of the same order. Because of the large patient load, the government of India sent out a directive in 1992 that all ^{60}Co machines would be operated two shifts (16 hours) each day. As a result, when machines developed minor problems that were not attended to, major breakdowns and consequent losses of machine time occurred.

Maintenance Problems: In most developing countries machine suppliers cannot afford to maintain service facilities. As a result spare parts and service are prohibitively expensive. Institutions do not recruit engineers for maintenance purposes. In India, because employment of medical physicists at such facilities is mandatory, these physicists attend to most of the minor problems associated with the accelerators. Government owned hospitals find it difficult to purchase spare parts because of burdensome administrative procedures and the absence of funds. Most countries in the region do not even have a sufficient number of trained medical physicists and hence depend completely on the manufacturers. Thus the maintenance problems are acute in countries where local service centers do not exist.

Realizing the need for trained personnel, India initiated a one-year postgraduate program at Bhabha Atomic Research Center, Bombay, in 1961 in collaboration with WHO to train medical physicists. This has helped a lot in ensuring quality assurance and maintenance. Some developing countries, under the IAEA fellowship program, have also utilized this training. More countries should apply to participate in this program, which can accommodate 10 to 12 students each year. Since developing countries have accepted medical physicists into their radiotherapy teams, a liberal provision of medical physicist will help to overcome most of the maintenance problems.

Economics of Developing Countries in Relation to Health Care: C. Nunan

The incidence of cancer in the U.S. is about 470 per 100,000 inhabitants, and similar numbers apply in Europe. The incidence of cancer per 100,000 inhabitants is only about one-quarter to one-third of this figure in developing countries.

Of all the cancer patients in the U.S.A., about one-half receive radiation therapy. Half of these are treated with curative intent, and half of these show no evidence of disease after 5 years. Hence about one-eighth of all cancer patients are "cured" by radiation therapy. In developing countries, the cure rate may be worse because patients are typically identified with more advanced diseases. Thus, even the medical practitioners in developing countries may view the benefits of radiation therapy as primarily palliative, i.e. for transient relief from symptoms.

Developing countries have per capita Gross National (Domestic) Products that are about 4% of that in the U.S.A. For example, in India a person would have to work 2000 years to earn the value of one low-energy accelerator while a person in the U.S.A. would need to work 25 years. The money to purchase equipment and services from outside most countries is frequently quite limited because it is already committed to paying interest on loans or for the purchase of other essentials. The infrastructure does not exist to manufacture accelerators within most developing countries.

Because of the severe economic constraints in the developing countries, the emphasis should be placed on the entire radiation therapy facility, not just the accelerator. The patient throughput of such facilities can be increased markedly through automation of the accelerator, addition of a multileaf collimator, modification of the patient couch, and arrangement of the facility to accommodate patient setup outside the treatment room.

The purchase price of a low-energy accelerator is only a fraction of the total facility costs. The operating costs of a present-day linear accelerator may be very high, depending on its complexity. A specially skilled engineer may be needed in some facilities on a standby basis to make repairs and ensure uninterrupted availability for patient treatment. The rest pays for the building and other equipment, such as for treatment planning, simulation, brachytherapy, etc. In addition, there is a large cost to train the staff (radiation oncologists, physicists, radiation therapists, dosimetrists and engineers).

With proper treatment planning, any beam having an accelerating potential of 2 MV or greater will permit delivery of superior dose distributions. The goals of ruggedness and simplicity of the accelerator proper may be achieved through the choice of a low-energy machine.

Instead of concentrating on machine cost, perhaps one should concentrate on patient throughput. The number of external radiotherapy patients that can be treated per day in a facility can be increased by a least a factor of 2 through automation. The actual beam "on" time to deliver 2 Gy to the tumor at depth can be less than 1 minute per day per patient. Yet about 12 minutes total time per patient is spent in the U.S. by the radiation therapist.

There is also a need to address the question of machine maintenance. Failures relate to things that move and can become stuck, such as the source, gantry and couch. Because of organizational and funding problems, simple electrical and mechanical failures often cannot be repaired by local personnel in developing countries. Tables 10 and 11 show the distribution of service problems, and Table 12 lists the distribution of parts replaced for a linac model in wide use but no longer manufactured.

Table 10

A. Clinac 4 Service Problems Similar to ^{60}Co
(C. Nunan. Data from Varian Associates)

Subsystem	Percent of Total Repairs
Patient Table and Support Assembly	13
Pendant	7
Gantry Rotation and Jaws (Drives, Readouts)	20
Field Light, Optical Distance Indicator	10
Wedge and Shadow Tray Plugs	4
Timer	2
Miscellaneous	2
Total	58

B. ^{60}Co Service Problems Additional to Those of an Accelerator
(C. Nunan. Data from Varian Associates)

Source Mechanism Partial or Total Failure
Periodic Source Replacement

Table 11

Clinac 4 Service Problems Additional to ^{60}Co
(C. Nunan. Data from Varian Associates)

Subsystem	Percent of Total
HVPS Diodes	12
Modulator (PFN Tune, De-Q* and Main)	2
Magnetron (and Magnet)	1
Circulator	1
Accelerator Guide (Gun, Target, Rad Rot)	-
Dosimeter System	3
PC Boards	6
AFC	3
Water System (Leaks)	6
Gas System (Gauges, Leaks)	3
Hoses, Cables	2
Pulse Transformer	-
PFN Capacitors	-
Miscellaneous	3
Total	42

(*Q = cavity quality factor)

Table 12

Parts Replaced per Year per Clinac 4

(Averaged over 287 machines in 1991)
(C. Nunan. Data from Varian Associates)

Part	Percent of Total	Part	Percent of Total
Accelerator Guide	1.2	Ionization Chamber	0.3
Magnetron	1.8	Patient Support Assembly	1.2
Magnetron Magnet	1.0	PSA Down Brake	4.0
rf Water Load	0.3	PSA Turntable Lock	0.3
Circulator	1.5	PSA Cables	1.5
rf System Parts	3.0	PSA misc. parts	3.3
Gas Pressure Regulator	1.0	Pendant	0.5
Main Thyratron	5.9	Pendant Springs	5.2
De-Q Thyratron	2.2	Pendant Cables	1.8
Pulse Transformer	0.3	Console Control Relay	4.4
Pulse Cables	2.2	Console Other Parts	8.1
H.V. Diodes	1.9	Position Readout Parts	1.0
Gantry Motor	1.9	Water Pump	1.5
Gantry Harmonic Drive	0.3	Heat Exchanger	1.2
Gantry Torque Limiter	0.7	Rotary Joints	2.7
Gantry Cables	1.5	Barber-Coleman	0.3
Gantry Angle Encoder	1.9	Penn Valve	1.5
Jaw Motor	0.7	Water Pressure Switch	0.5
Collimator, Misc. Parts	6.4	Water System Gauge	2.7
Collimator Rotation Motor	1.8	Water System Parts	1.5
Radiation Head Cables	1.0	Lasers	0.3
		Printed Circuit Boards	18.0

Summary By Subsystem

Subsystem	Percent of Total	Subsystem	Percent of Total
Gantry Rotation	6.3	Microwave System	9.8
Collimator	9.9	Pulse Modulator	12.4
Patient Table	10.3	Water System	11.8
Pendant	7.5	PC Boards	18.0
Console	13.4	Miscellaneous	0.6
Total	47.4	**Total**	52.6

SESSION II: RADIOTHERAPY EQUIPMENT PERFORMANCE REQUIREMENTS

Moderator: H. Svensson
Discussion Leader: T. Landberg
Secretary: A. Brahme

Medical requirement considerations

Under optimal conditions it is expected that 50%-60% of all patients diagnosed with a cancer will receive radiotherapy either at the time of diagnosis or later during the course of the disease. Two-thirds of the radiotherapy treatments will be with a radical intent, and one-third with a nonradical (palliative) intent. In cases of restricted resources, palliative therapy will be limited.

At present, the majority of patients receiving radiotherapy belong to one of the following categories:

(a) Breast cancer
(b) Lung cancer
(c) Gynecological cancer
(d) Head and neck cancer
(e) Bladder carcinoma
(f) Malignant lymphoma
(g) Cancer of the prostate
(h) Skin cancer
(i) Other skin malignancies frequently HIV-related

It is expected that during the next decade, the need for radiotherapy for these different diagnoses will not change significantly. Expected changes in diagnostic procedures, including screening for early cancer, may lead to a substantial increase of the need of radiotherapy for a given population size. Increase in the average age of the population will also increase the need.

For dose planning purposes, the cancer diseases can broadly be categorized into three groups:

1. Superficial tumors (e.g. skin tumors)
2. Semi-deeply situated tumors (e.g., head and neck tumors and breast cancer)
3. Deep seated tumors (e.g. pelvic tumors)

For the different types of locations, there are different demands on the build-up and the depth-dose characteristics of the beam(s) to be used. Some of these characteristics can be modified by special means (e.g., bolus to decrease the effect of build-up for superficial tumors).

A compromise between clinically optimal beams and realistic accelerator performances was sought in the requirements.

Approximate time schedule to develop a new treatment unit

• Raising money for the project	2 years
• Development of prototype unit	2-3 years
• Radiation, physical and clinical tests	2-3 years
• Extra time for brand-new design	2 years

- Total time before serial production

Moderate changes	6-7 years
Brand-new design	8-9 years

Clinics interested in such units

- Developing countries
- Europe
- Canada, Japan, Australia, etc.
- Some clinics in the U.S.A.

Performance Requirements

To reduce complexity and improve safety a single-energy photon unit without electrons is recommended. (It is assumed that there is access to at least superficial x-ray machines with energies between 100 and 300 kV for the treatment of tumors up to a depth of 3 cm.)

Treatment time (average 2 fields/patient)	10-15 min/patient
Patients treated/8 hours day	32-48
Dose rate at isocenter (depth of dose maximum)	0.8 Gy/min Minimum, 2-3 Gy/min Recommended

Mechanical data

Isocentric design	recommended
Isocentric height above floor level	≤130 cm, preferably 115 cm
Isocentric clearance (with all devices)	≥35 cm
Source-isocenter distance	≥80 cm, preferably 100 cm
The floor surface should preferably be flat, i.e., no pit	a small depression is acceptable
Collimator jaw and distance indication	mechanical or electrical with mechanical backup

Couch motions and radiation field size

Isocentric, rotation	preferred
Angle of rotation	±90°
Lateral range	±20 cm
Vertical range	70 cm below isocenter preferred.
Field sizes surface	up to 42 cm x 42 cm at the of a 25 cm thick patient, should be available from above with lowered table
Maximum field size at isocenter	30 cm x 30 cm

Radiation Beam Quality

About 65% of all radiation therapy is performed using two opposing fields, and there is a strong preference for the higher energy (6 MV) instead of using more than two fields with lower energies (e.g., 2.5 MV equivalent to ^{60}Co). Beam quality is defined in a parallel-opposed beam configuration for a 10 cm x 10 cm field size and a patient thickness of 25 cm using equal beam weights. In this configuration the following should hold

• Depth of superficial 90% isodose (to treat superficial lymph nodes)	≤5 mm
• Dose value in hot spots relative to central target dose (to avoid fibrosis)	≤115%, and preferably ≤ 110%
• Penumbra width	<1 cm, and preferably <8 mm
• Uniformity over 80% of field (IEC)	±3%

Devices to be available for radiotherapy treatment

- Light indication for field size with central axis indication
- Distance indication with mechanical backup
- Isocentric indication with mechanical backup
- Wedges 15°, 30°, 45°, 60°
- Light field preferably visible after insertion.
- Orientation and wedge angle interlock.
- Shadow tray(s) for standard and customized beam blocks.
- Possibility to take megavoltage port films

Safety

- Compliance with FAO/IAEA/ILO/OECD-NEA/PAHO/WHO International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, as well as national and local safety regulations.

Quality and Maintenance

• Long-term stability	fundamental
• Operation up to 40°C at high humidity	feasible
• Operation without downtime	≥95%
• Service interventions that interrupt scheduled treatment	< 1/month
• Preventative maintenance	< 4/year
• Self diagnosis	recommended
• Component potential failure status read-out	recommended

Serviceability/Reliability Specifications

Preventative Maintenance

There shall be specified intervals for preventative maintenance. The integrity of the machine shall not be guaranteed if the manufacturer's schedule is not followed. These specifications may involve procedures in addition to regular (daily/weekly) quality assurance checks on the equipment.

Failures Requiring Intervention

These shall be classified according to the level of skill required to rectify the fault. With good education programs, some of these interventions may be handled "in house."

- **First-Line Failure**
  A local engineer trained by the manufacturer or the manufacturer's local representative could localize the problem to the unit level using standard diagnostic procedures and in most cases isolate the fault to the printed circuit board level. May solve 90% of the problems.
- **Second-Line Failure**
  A regional manufacturer's engineer would normally address failures at this level and would expect to solve 80% of the remaining problems.
- **Third-Line Failure**
  A senior level from the manufacturer's head office would be called to address faults at this level.

Mean Time Between Failures

• First-line failure	> 3 months
• Second-line failure	> 1 year
• Third-line failure	> 10 years

Target Planned Maintenance Schedules

- 1 day required every 3 months
- 3 days required every year

Spare Parts

A stocking strategy should be defined to support the maintenance requirements.

• First-line repairs	on site
• Second-line repairs	regional
• Third-line repairs	manufacturer

SESSION III: REVIEW OF NOVEL ACCELERATOR PRINCIPLES

Moderator: C. Borrás
Discussion Leader: C. Nunan
Secretary: J. Stovall

Response to Medical Requirements

The medical performance requirements that are relevant to the design of equipment can be divided into three general categories relating to mechanical, radiation, and reliability issues. To evaluate the appropriateness of a specific technology, it was found desirable to translate the medical performance requirements listed in the preceding section into a set of specific quantitative engineering requirements. A listing of technologies of interest and their relative order of priority for investigation follows.

Mechanical Engineering Requirements

Mechanical requirements include an isocentric radiation source, at a distance equal to or greater than 80 cm SAD (preferably 100 cm SAD) with an isocenter not more than 130 cm above the floor (preferably 115 cm), with a flat floor surface. (A small dip in the couch turntable is acceptable provided it does not extend beyond the width of the couch.) This implies a rotating gantry design that must provide for a clearance from isocenter with all devices attached of at least 35 cm. Displays and readouts may be mechanical or digital. For reliability, mechanical backup of digital readouts would be desirable. Although an isocentric couch is preferred, it must provide sufficient range of vertical motion such that field sizes of at least 42 cm x 42 cm can be obtained at the entrance skin surface for a 25 cm thick patient. This means that for an 80 cm isocentric unit, the couch vertical travel range below isocenter must be at least 57 cm, and for a 100 cm unit, this range must be 65 cm. The field size at isocenter is 30 cm x 30 cm in both cases. An increase in field size at isocenter to 35 cm will result in maximum field sizes of 46 cm for the 80 cm unit and 49 cm for the 100 cm unit for the same ranges of couch vertical travel. Couch travel of a few (2 or 3) cm above isocenter is desirable.

Radiation Engineering Requirements

Radiation performance requirements that affect equipment design include a uniform flattened field of ±3% at a field size of 30 x 30 cm (35 x 35 cm preferred) at isocenter and a minimum dose rate of 0.8 Gy/min (2-3 Gy/min preferred). In the buildup region the 90% isodose should not be deeper than 5 mm, and using equally weighted opposing fields, for a 25 cm thick patient, the maximum dose ratio (dose at maximum over dose at axis $\equiv D_M/D_A$) should not be greater than 115% (110% maximum preferred) for a 10 x 10 cm field. The 90% requirement can be achieved over a range of effective photon energies by use of photon spectrum spoilers. The 110% or 115% limit for D_M/D_A is <u>the</u> major factor that determines the required effective photon energy. Approximate ratios of D_M/D_A as a function of energy, based on BJR-17 depth dose data, are listed in Table 13 for parallel-opposed, equally weighted 10 cm x 10 cm fields, for 20 cm and 25 cm patient thickness.

In addition, a number of environmental conditions should be considered in any new design. These include the availability of a stable power source (±15% power fluctuations should be expected) requiring consideration of voltage-independent power supplies, operation at temperatures above the dew point to prevent condensation on components, and difficulty with aspects of cooling-water supplies, which suggests use of closed-loop cooling systems or discharge to air-exchange systems. New equipment designs must conform to published safety and reliability standards of computer control systems and software interlocks.

Table 13

D_M/D_A Ratios for Various Beam Energies

				Patient Thickness	
	Depth (mm)		SSD	20 cm	25 cm
Machines	D_M	D_{90}	(cm)	D_M/D_A	D_M/D_A
^{60}Co	5	1.8	80	114%	127%
^{60}Co	5	2	100	111	123
4 MV	10	4	80	110	120
4 MV	10	4	100	109	117
6 MV	15	7	100	106	112
8 MV	20	9.3	100	104	110
10 MV	25	11	100	102	107

Similar information can be derived from Figures 3a and 3b, taken from WHO's Technical Report Series 644. Figure 3a shows the inverse of D_M/D_A as a function of thickness, and Figure 3b shows the number of nonopposed fields required to achieve a ratio of D_A/D_M equal to 1.5, as a function of the depth of tissue below the surface.

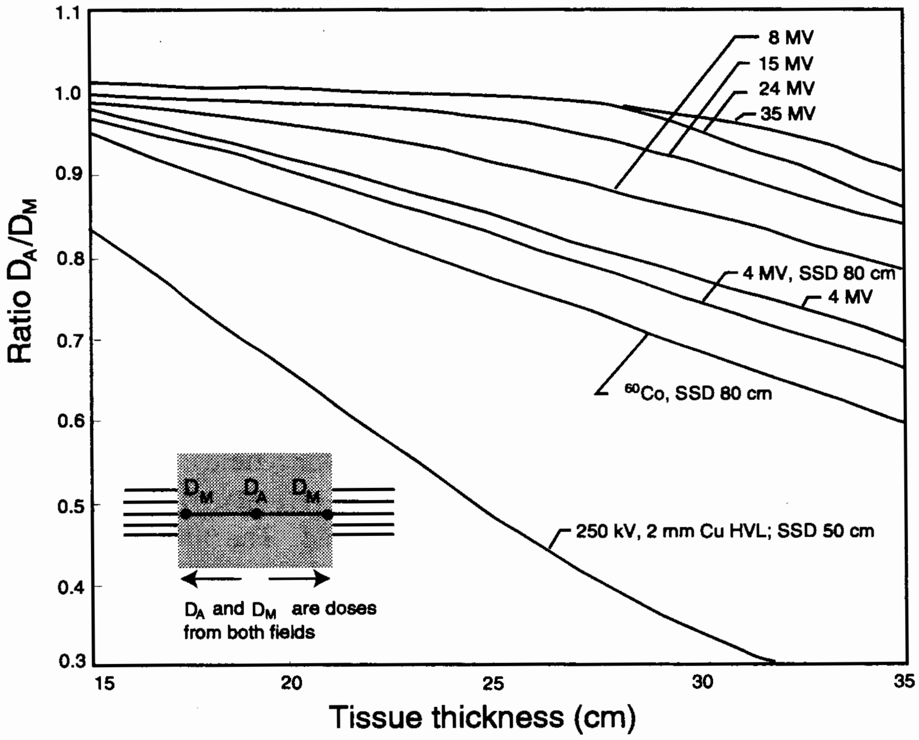

Figure 3a. Ratio D_A/D_M for two opposed fields 10 cm x 10 cm in area as a function of thickness of tissue, for various radiation energies. SSD 100 cm unless otherwise indicated.[4]

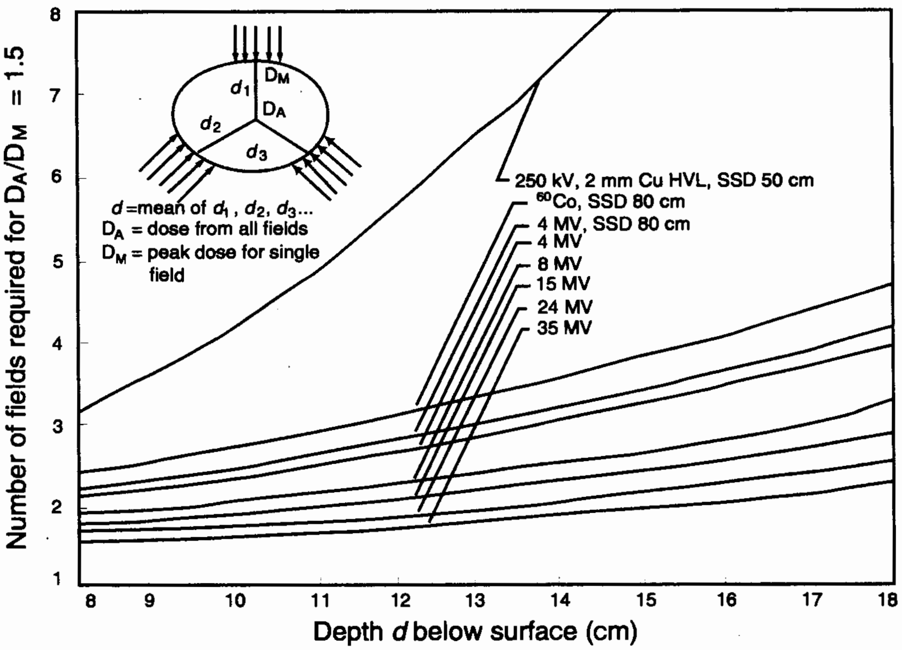

Figure 3b. Number of nonopposed fields required to achieve a ratio of D_A/D_M equal to 1.5 as a function of depth below surface of tissue, for various radiation energies. SSD 100 cm unless otherwise stated.[4]

Both sets of data show that D_M/D_A increases rapidly with increasing patient thickness. To meet the maximum limit of 115% D_M/D_A for a 25 cm thick patient, ^{60}Co and 4 MV, using common field filtrations, are inadequate for parallel-opposed fields. About 5 MV is required to meet 115% with SSD treatments (patient couch moved); about 6 MV is required to meet 115% with parallel-opposed isocentric treatments (tumor stationary on gantry axis). About 8 MV is required to meet the preferred 110% D_M/D_A limit. As shown in these figures, more than two fields are required to limit D_M/D_A with machine types of lower energies. Translated into engineering design requirements and assuming 100 cm SAD, this means that the equipment must be capable of providing electron beam currents of about 100 μA at 6 MV or 200 μA at 4 MV, to meet the above preferred radiation conditions at 3 Gy/min with an adequate margin for reliability.

Due consideration should also be given to the choice of target and flattening filter design, as well as how electron contamination is controlled, as all these factors will significantly affect the quality of the photon beam.

Reliability Engineering Requirement

Reliability requirements include up times of ≥95%, service interventions (because treatments cannot continue) of less than 1 per month and preventative maintenance of less than 4 times per year. These requirements suggest that new equipment designs must seek to reduce the number of components and/or consider highly modular designs.

Alternative New Technical Approaches Considered

The various accelerator technologies considered were subjectively ranked A, B, or C depending upon their practicality and likely ability to meet the above requirements.

Ranking	*Definition*
A	Technology is most likely to meet the requirements and merits further exploration
B	Technology is probably relevant
C	Technology is not likely to meet the requirements, and is not recommended for exploration at this time but should be retained for future reference.

Category A Technology

Microwave linear accelerator (Figs. 4a and 4b)

Standard microwave linear accelerators are the most common accelerators for x-ray therapy in the range of 4 - 25 MV. A considerable amount of development and experience has been invested in this technology, and it will continue to be the standard against which other technologies will be compared for the foreseeable future.

Developers and manufactures should be encouraged to improve the performance of microwave, linear-accelerator-based machines particularly in the areas of component and system reliability, maintainability, and simplicity of operation.

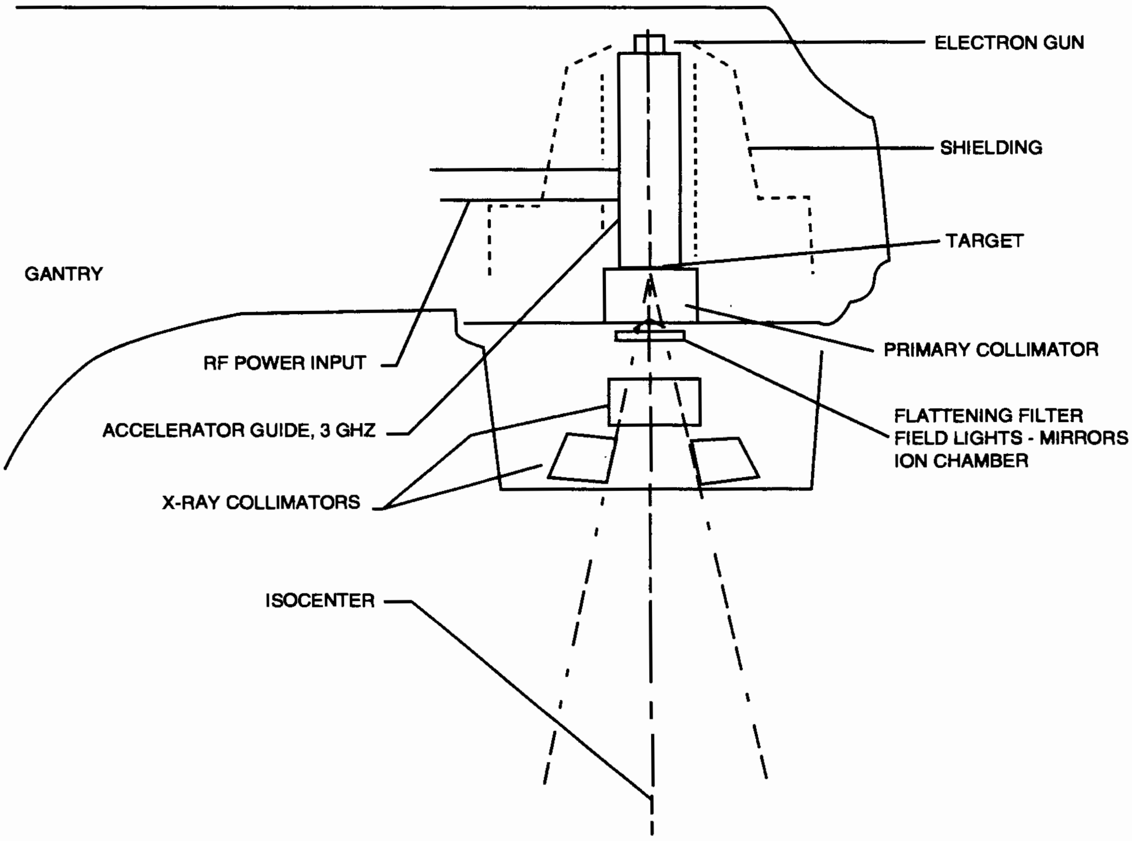

Figure 4a. 6 MV linac in-line accelerator.

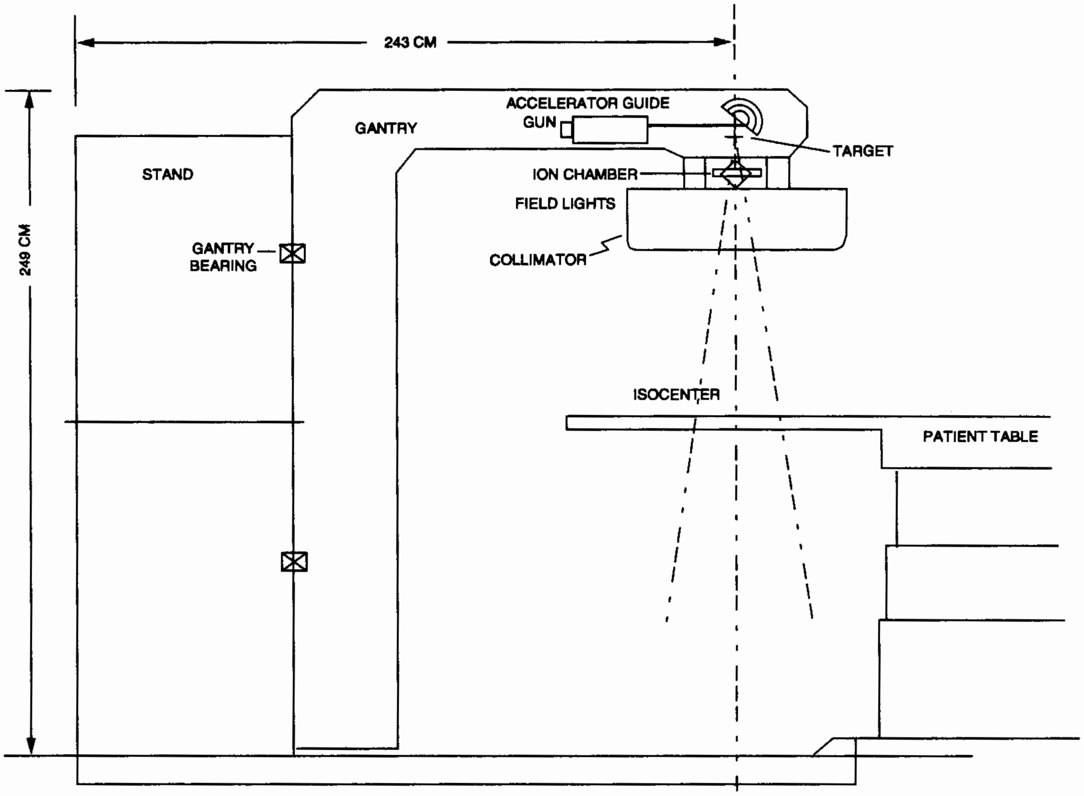

Figure 4b. 6 MV Linac, 270 degree bent beam.

Microwave power source combined with a linear accelerator (2 beam klystron/linac accelerator) (Figure 5)

The concept of resonantly coupling the rf power source directly to the linear accelerator offers the possibility of eliminating many of the active rf components that comprise machines of present design. This technique makes use of a self-excited klystron that is driven by a low-voltage but very high-current electron beam. Since this device starts from noise, it is technically an oscillator rather than a traditional klystron amplifier. For this reason, it requires neither an rf signal nor any type of frequency control.

The output cavity would be resonantly coupled to a standing-wave, linear accelerator operating in the stable $\pi/2$ mode. Unwanted modes are suppressed by controlling the quality factor of the unexcited coupling cavities. Calculations have shown that such a machine can be designed to be very stable over long pulses. Beam powers exceeding those required for therapy would be feasible.

Such a combined function device would not require a magnetron, rf window, waveguide, circulator, load, rf source or frequency control. It would require either a high-voltage modulator or a pulsed cathode gun on the klystron oscillator. It would require two electron guns, but it would decrease the overall complexity and component count, presumably increasing reliability while reducing maintenance.

Low-energy microtron in line with radiation head. (Figure 6)

The circular microtron consists of a single accelerator cavity placed in a constant and uniform magnetic field. Operating at S-band (10 cm), microtrons efficiently produce a well-collimated beam of electrons with a small energy spread with energies from 2 to 30 MeV. Extensive

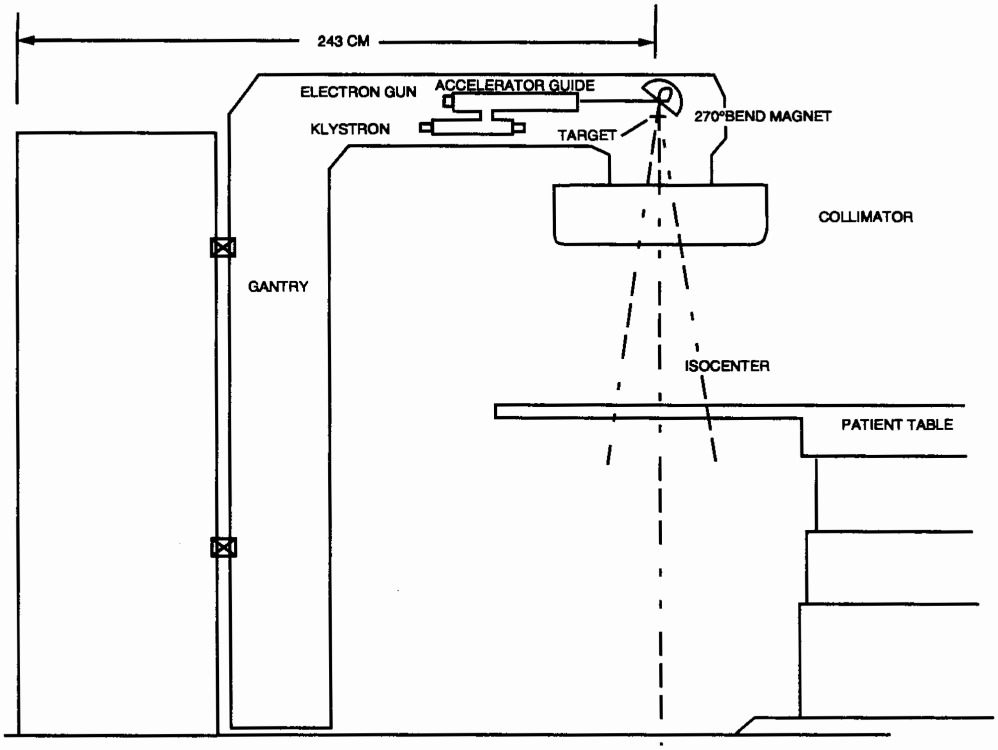

Figure 5. Integrated klystron/linac.

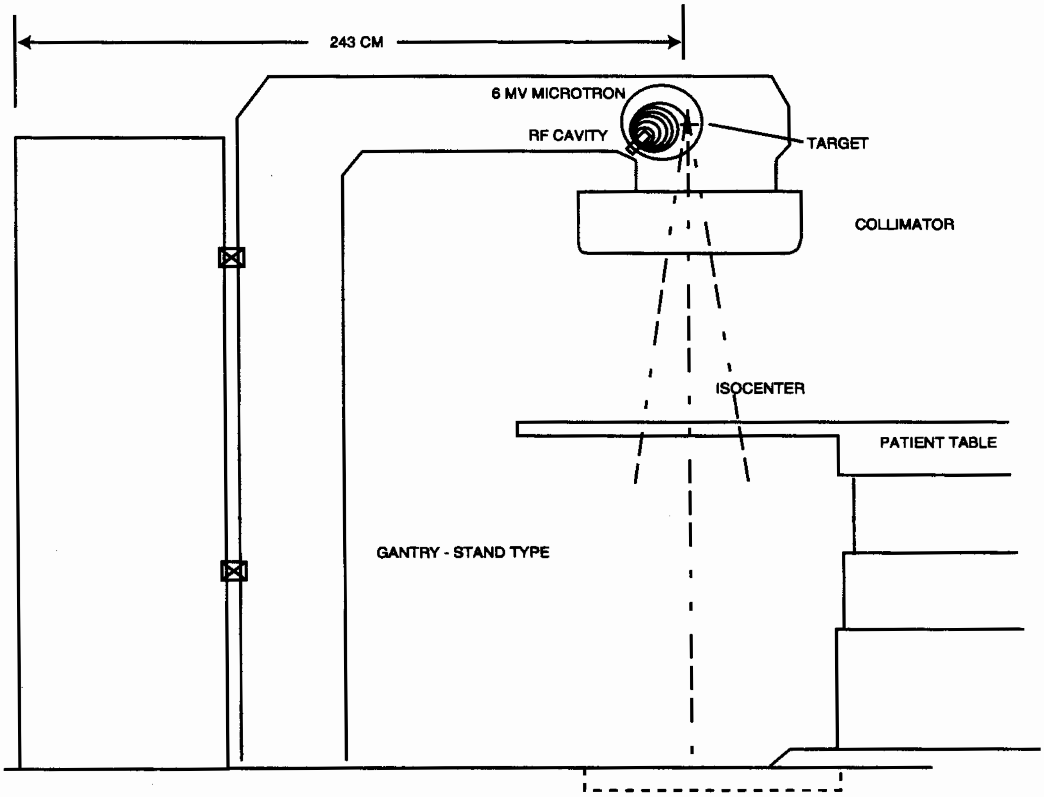

Figure 6. 6 MV microtron.

gained in building these accelerators for medical purposes has led to the development of 22 MeV advanced electron and photon machines and a compact 7 MeV photon medical microtron.

Present microtron technology is directly adaptable to meeting the beam performance requirements specified above. Directly coupling of the rf power source (magnetron) to the microtron cavity, if possible, offers the same advantages listed above for linear accelerators: simplicity and reduced component count. The presence of the magnet provides the possibility to use it to obtain a very pure photon beam without electron contamination by operating it as a purging magnet.

Microwave power source combined with accelerator cavity

The magnetron is the rf power source of choice in today's microwave electron accelerators, capable of meeting the present beam specifications. Improvements in the rf power systems offer the possibility of significantly improved reliability and maintainability of therapy units.

To reduce the complexity of the modulator, a concept was introduced of a microwave source in which the magnetron and the magnet are integrated and the magnet is pulsed using a dc power supply. Magnetrons in which the magnet rather than high-voltage is pulsed offer a potential solution to the unreliability of today's thyratron-based pulse modulators.

The development of an integrated klystron and linac system or an integrated magnetron and microtron resonator system would simplify the design of medical accelerators and lead to increased efficiency and stability of the machine. Built with a common vacuum system and physically connected, even brazed together, these units could be changed as integrated components.

The development of modular systems will require a dedicated research effort, but in view of the large numbers of accelerators needed, it will eventually lead to cheaper and simpler accelerators requiring less tuning, servicing, and adjustments in operation.

Higher frequencies than 3 GHz

Microwave linear accelerators and microtrons operated at higher frequency (> 3 GHz) offer the advantages of compactness and weight reduction. One of the present limitations in pulsing higher frequency (X-band) accelerators is the reliability of conventional magnetrons at those frequencies. Reliable X-band magnetrons of the coaxial design are presently used in military applications but are expensive. Further development is encouraged to bring down the cost of these rf power sources.

Modular electron accelerators (Figure 7).

Modular design of the accelerator and components may increase reliability and simplify service activities.

Category B Technology

Betatron in radiation head (Figure 8)

With the aim of designing an alternative medical accelerator, it is worth looking into the possibility of developing a betatron operating in a pulsed or high-frequency mode, although it is difficult to produce 0.5 kW beams at energy 6 MeV, because the current of these accelerators is limited.

It would be necessary to establish the magnet frequency that can be used, but about 10 kHz instead of the conventional 180 Hz will be required for an adequate dose rate flattened over large fields. A laminated flattening filter can be placed in the fringing field, which then would sweep out Compton electrons produced in the flattening filter, providing a lower skin dose. The target size is generally very small, so methods for cooling should be studied.

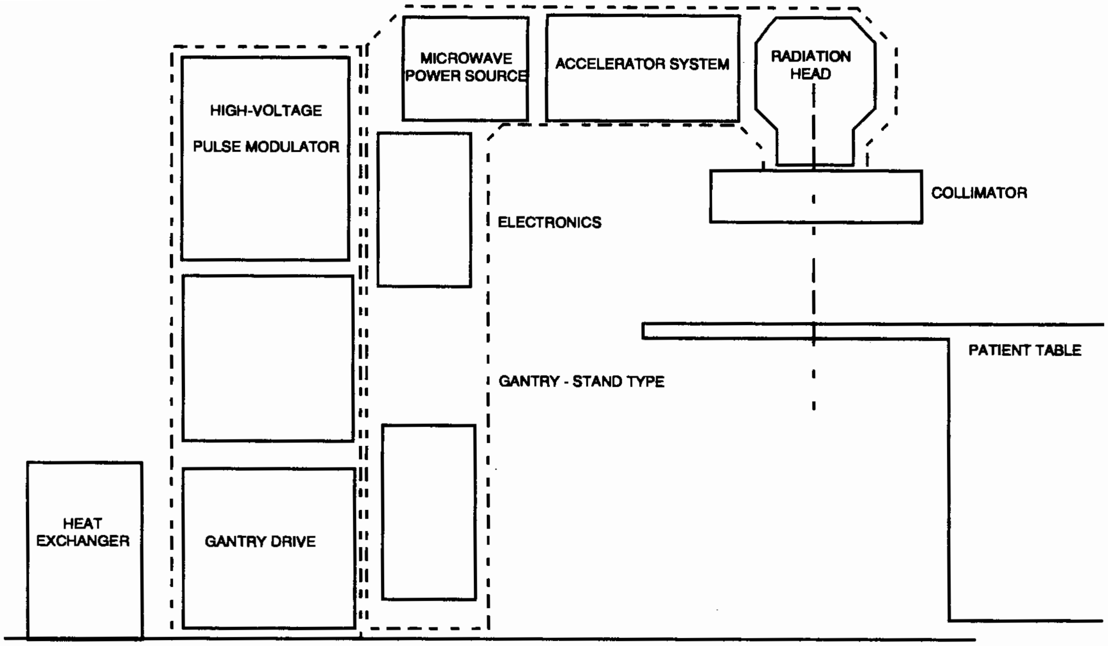

Figure 7. Modular linac.

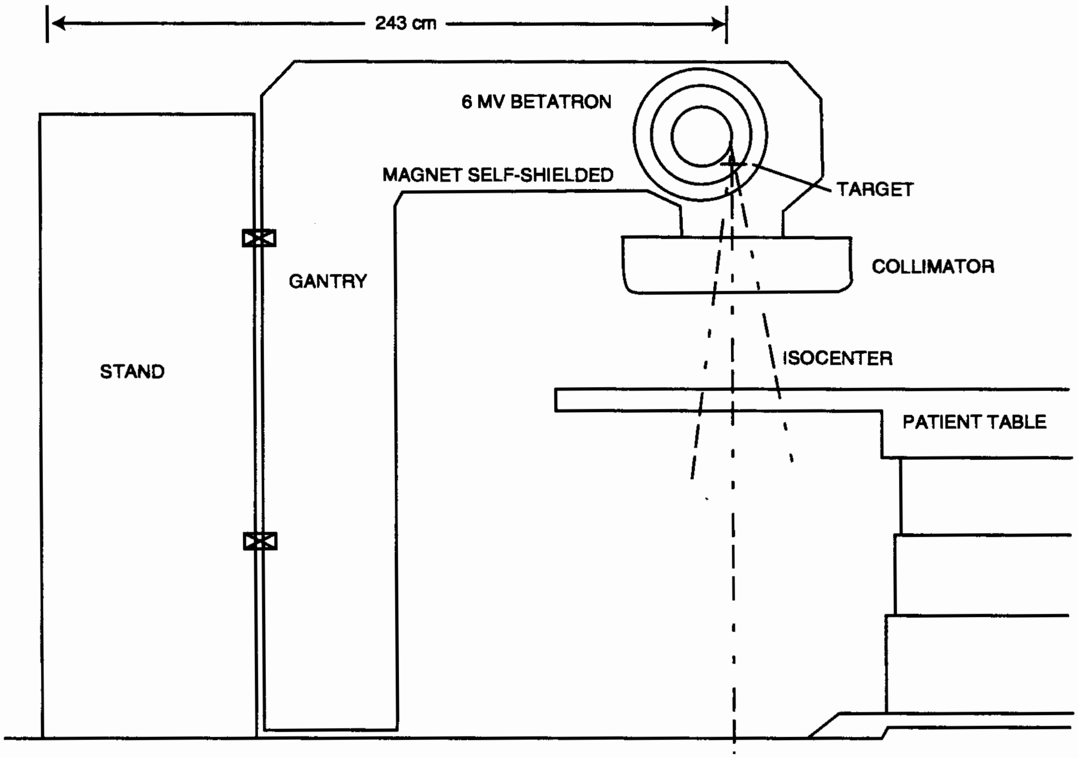

Figure 8. 6 MV betatron in radiation head, 10 kHz self-shielding magnet.

Figure 8 illustrates a gantry system with a low-energy betatron. Either a multileaf collimator or a standard collimator tray for shadow blocks and a wedge holder are needed.

Rhodotron. (Figure 9)

The cw rhodotron is an rf accelerator designed by the Research and Development Department of France Atomic Energy to produce a 20 kW electron beam at 5 MeV for food sterilization. The prototype is powered by rf power at 300 MHz. It uses a half-wave coaxial cavity in which the electron beam is reflected by external magnets to create multiple passes in the mid-plane of the structure The electrons are accelerated on each pass. It operates cw, hence obviating the high-voltage pulse modulator. The low operating frequency permits use of highly efficient and reliable gridded tubes in the rf power source.

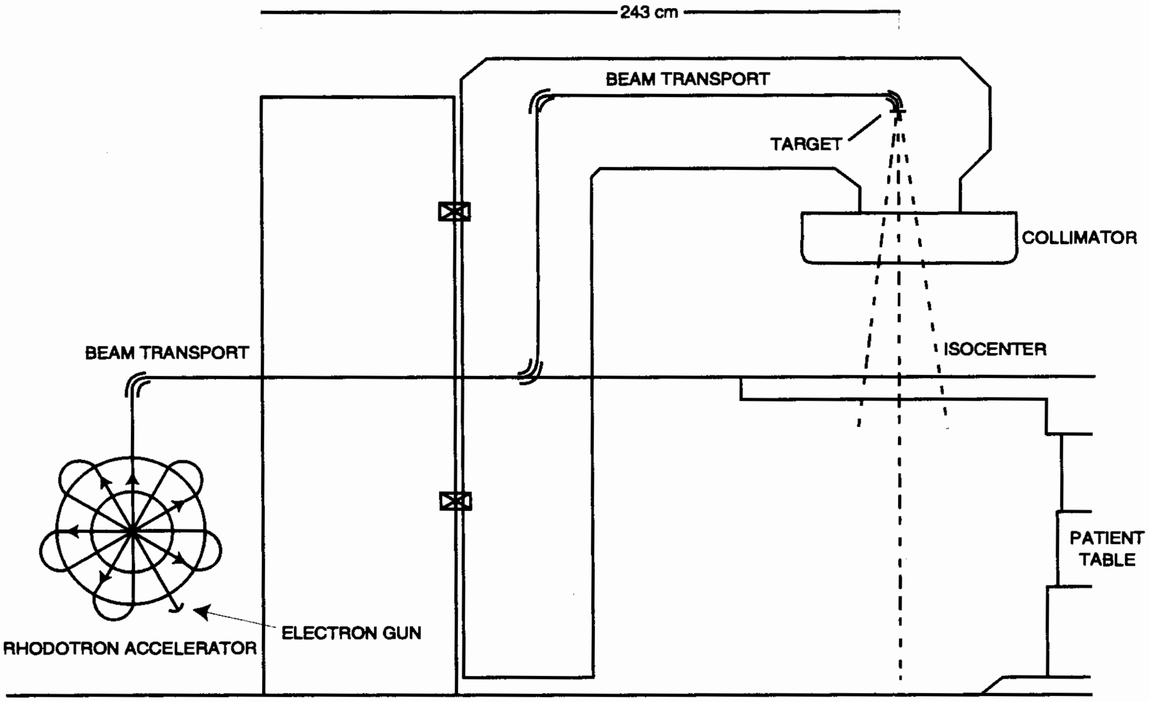

Figure 9. 6 MV cw rhodotron, 0.5 MV per cavity gap.

Continuous wave rf linac or microtron (Figure 10)

These devices are considered as alternative accelerator designs because their rf systems are simpler than those used in pulsed devices. In these continuously emitting systems the pulse modulator and step-up transformer are replaced with a more conventional and reliable dc power supply. In addition, rf breakdown in the waveguides and accelerator is less of a problem.

Of the two devices, the microtron has advantages over the linac. First, it can attain 6 MV with the same rf system with which the linac achieves 2 or 3 MV. Second, it is much smaller, only 30 cm in diameter, as compared to 1.78 m long for the linac. The disadvantage of the microtron is that it requires a magnet. Both devices use a 50 kW, 915 MHz cw magnetron as rf source. The microtron has 20 turns. The linac could deliver a 4 or 6 MV beam by reflecting the beam in a

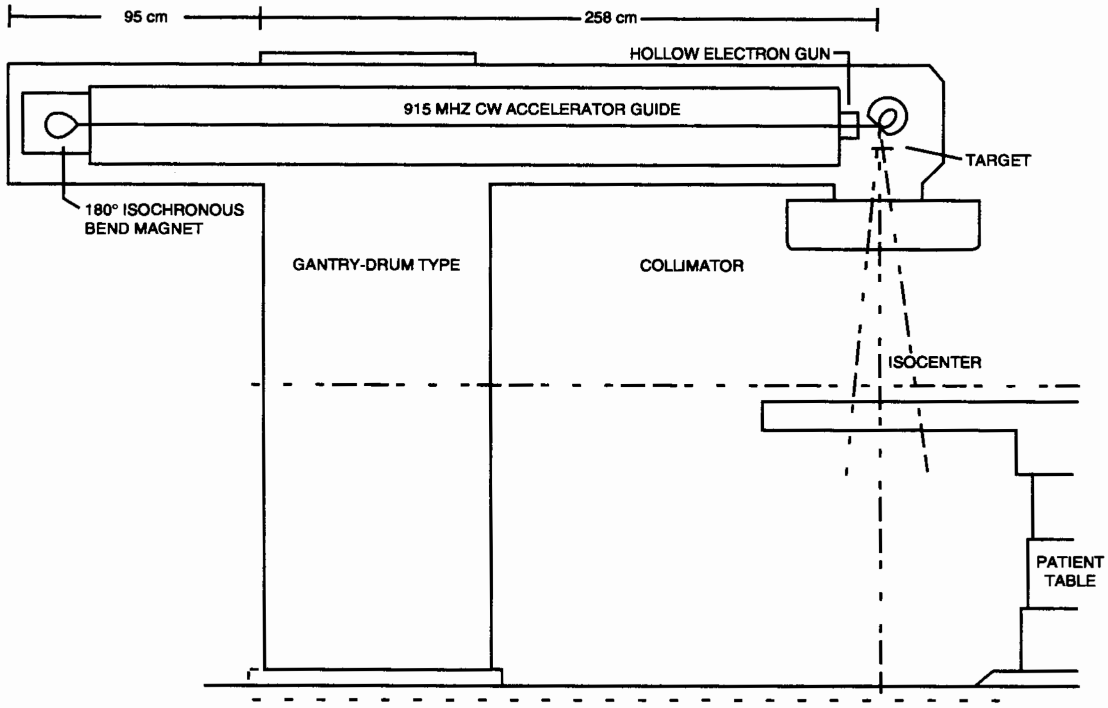

Figure 10. 6 MV cw linac, 915 MHz, reflected beam.

180 degree isochronous magnet, back through the standing wave accelerator guide in reverse phase. These devices require more power from the supply mains than the other accelerators.

dc Accelerators

Cascade Voltage Multiplier (Figure 11)

Individual 30 kV stages consist of capacitors and rectifiers that are stacked, for example, 100 of them are needed to provide 3 MV dc. This stack is supplied power in series through sequential capacitors from a transformer at ground. An electron beam acceleration column passes through the stack of stages. The outside dimensions are about 1.5 meters maximum diameter and 3 meters long for 3 MV. Sulfur hexafluoride gas at about 4 atmospheres may be required for insulation.

Laddertron or Pelletron Electrostatic Accelerators

These are examples of a modern chain-charged electrostatic accelerators that offer very high reliability as well as improved precision of output energy. Reliability has been improved by the use of shielding around electrical and electronics systems, and these machines can now be fully computer controlled. Transport of the output beam to more than one treatment room would be possible. The output beam current would be limited at present, but there is a possibility of increasing this to a level suitable for a therapy facility.

Nested High-Voltage Generator (NHVG)

An individual 60 kV power supply consists of the secondary winding of a transformer, a rectifier, and a storage capacitor. It is surrounded by an electrical shield, hence forming a "nest." To provide 3 MV dc a series of such nests are stacked up, for example 50 of them. This stack is supplied with alternating current (ac) power in parallel from a single cylindrical primary winding. An electron beam acceleration column passes through the stack of nests. The outside dimensions would be about 60 cm diameter and 3 meters long for 3 MV. Solid insulation is used.

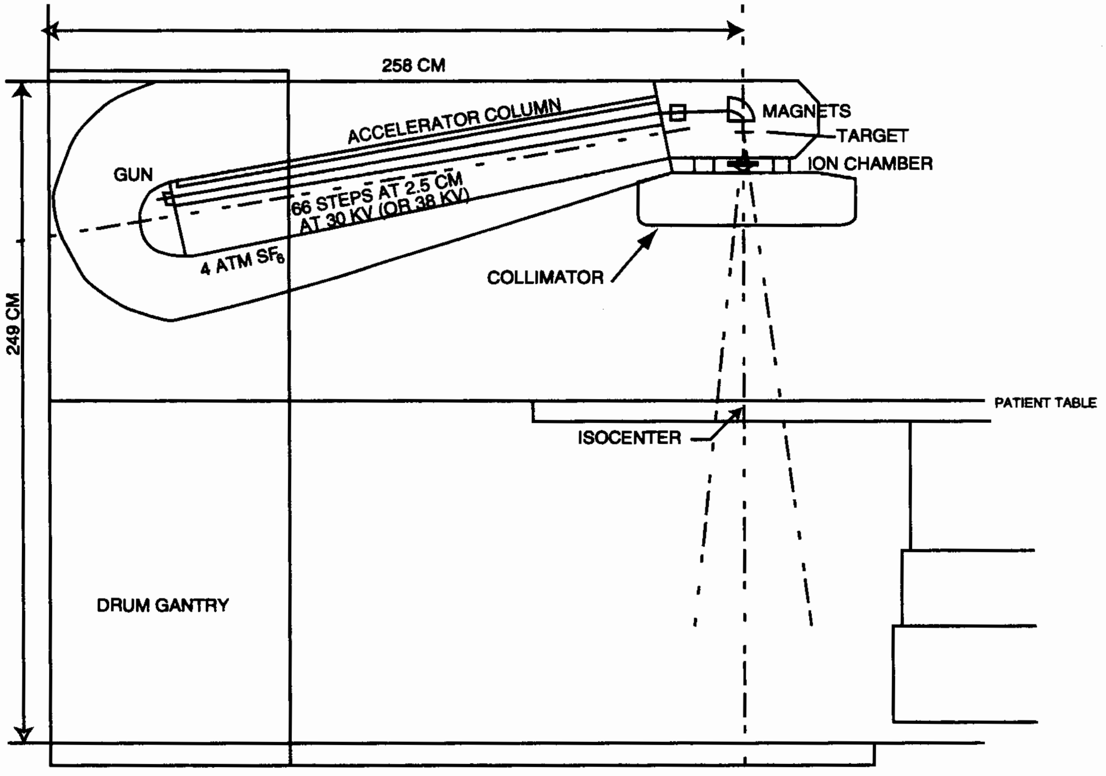

Figure 11. Cascade dc accelerator, x-rays filtered to 3 MV penetration.

Transformer-Coupled, High-Voltage Generator

A common term is insulated core transformer or ICT, in which a series of secondary transformer windings form a stack, which is driven by a primary winding. An electron beam acceleration column is separate from this generator and is connected to it by a multiple insulated transmission line. Alternatively, the acceleration column can be internal to the housing for this generator.

Category C Technologies

Plasma wave accelerator

This principle, which was proposed more than a decade ago, is reported recently to have been successfully demonstrated in laboratory experiments at the University of California in Los Angeles with the acceleration of externally injected 2.1 MeV electrons to 9.1 MeV. Two copropagating laser beams were used to drive a relativistic plasma resonantly. The resulting ultra-high-gradient electric fields accelerated the externally injected electrons. Future possibilities of the technology could include the production of compact sources of x-rays for medical applications.

Induction linac

This nonresonant accelerating structure uses a series of inductively coupled, ferromagnetically loaded (in the form of laminated iron or ferrite), independently driven accelerating cavities arranged in a straight line. A modulator drives each cavity, which acts as a transformer, with the particle beam constituting the secondary winding. The modulator consists of a pulse-forming network and a spark-gap switch (or magnetic modulator) capable of delivering high-current and -voltage pulses ranging from several tens to hundreds of kilovolts. The beam is timed to pass each cavity when the change of magnetic flux is produced by the voltage pulse applied to the driving loop. The particles are accelerated in the induced electric field across the gap.

The method is capable of accelerating very large beam currents in the range of 100 A to 100 kA (in a single pulse). Usually, a Marx generator is used to charge the pulse-forming network or the transmission line. The pulse duration is of the order of a few tens of nanoseconds to hundreds of nanoseconds, while the repetition rate is tens of Hz. The energies of the accelerated particles are in the 1-50 MeV range, and the mean accelerating gradients range from 0.3 to 5 MV/m. Almost all the induction linacs presently in operation are electron linacs. Because of their inherent capacity to deliver very high-current short pulses, induction linacs are used in pulse radiography, as simulators for very high-power radiation interactions, and for the production of intense neutron pulses. Their limitations are size, pulse rate, and beam focusing onto the x-ray target. A typical performance rating for an induction linac might be 4 MV, 10,000 ampere electron beam, 50 nanosecond pulse duration, yielding 500 microamperes of average beam current at 1 pulse per second repetition rate translating to an x-ray source delivering 7.5 Gy/min at 1 meter.

Interlaced accelerator structure

The interlaced linac is a hybrid composed of two standing-wave, side-coupled linacs. The accelerating cavities of these two linacs are generally interlaced so that odd cavities are all members of one linac while even cavities are all members of the second. Because adjacent cavities are electrically isolated from each other, their relative rf phases can be adjusted to almost double the effective energy gradient (40 MeV/m). In addition one linac can be used to control the low-energy beam dynamics while the field level of the second can be used to adjust the final beam energy independently over a broad range. Unfortunately, this advantage is achieved at the cost of increased power consumption.

Superconducting linac

In recent years great advances have been made in the development of superconducting materials that operate at temperatures as high as that of liquid nitrogen. Using such materials in the fabrication of accelerator cavities would, in principle, reduce the rf power requirement dramatically, permitting the cw operation. All high-temperature superconductor materials tested to date have had the physical and thermal characteristics of ceramic. As a result, they are difficult to form into the shape of accelerator cavities. In addition, they cannot conduct the heat away that is generated by the rf in the cavity wall and consequently tend to quickly loose their superconductive properties. Beryllium coating has not been tested at high rf power. Maintaining resonant frequency of high-cavity-quality-factor (high-Q) cavities against vibration is a challenge.

Small synchrotron

Electron synchrotrons have traditionally been used in research to attain beam energies in the GeV range and typically have very low extracted-beam currents. This circular machine accelerates the beam in one or more rf cavities. To avoid having to ramp the cavity frequency, a relativistic beam must be injected from a linac. As the energy increases, the magnets are ramped to maintain the beam in a stable synchronous orbit. Synchrotrons at low energies are quite feasible but combine the complexity of rf cavities, ramped magnets, and injection and extraction systems. One 70 MeV machine has been designed for radiation therapy applications.

Multiple low-power magnetron (e.g., microwave oven magnetron)

Low-power, inexpensive magnetrons are readily available for domestic microwave ovens. If a cavity of high enough impedance could be created, possibly the outputs of many such devices could be combined to produce the required power levels. If possible this would provide a secondary benefit in that the equipment would continue to function, albeit at reduced performance, if one of the devices fails. This technique is not considered technically practicable at this time.

Accelerator-activated, short-lived isotope

The idea is to produce a very short-lived radioactive isotope with a proton beam of a few MeV from a small cyclotron or proton linac. The isotope can be moved into position to irradiate the patient as is done with ^{60}Co units, then moved back into the proton beam position for reactivation. This reactivation can be done in between treatments while patients are being set up.

Overall Reliability Issues to be Addressed by all Designs

- Reduction in the overall number of parts or components.
- Provision for monitoring and measurement of photon dose rate and symmetry.
- Use of permanent magnets when practical such as for beam-bending magnets.
- Elimination of static discharges that might damage sensitive electronic components.
- Provision of adequate tools for accelerator repair.
- Provision of adequate spare parts as part of initial equipment purchase.
- Adequate design margins for component attrition.
- Minimization of lubrication requirements.
- Provision of information on anticipated failure frequency and monitoring of predictive component failures.
- Use of manual backup to electromechanical motion controls whenever practical.
- Adherence by manufacturer to ISO 9001 and IEC standards.

SESSION IV: SUGGESTED RADIOTHERAPY TREATMENT UNIT DESIGNS

Moderator: L. Lanzl
Discussion Leader: A. Brahme
Secretary: A. Rawlinson

Modular Design

Based on the various acceleration principles discussed in the previous section, a number of possible treatment unit designs have been suggested. It is clear from a very superficial study of the accelerator proposals above that a large number of constructional entities of the therapy units will be very similar. For this and other reasons, it is natural to recognize such modular components of a treatment unit.

Some of the modular components are interchangeable between treatment units presently in use such as heat exchangers and treatment couches. Some of the modular components of a treatment unit are schematically illustrated in Figure 7.

Other components like the microwave generator and the accelerator need uniform interface specifications to make them more readily exchangeable. It was recognized at the Consultation that good interface specifications for the modular components of a treatment unit would increase the flexibility for users to make their installations fit local requirements and needs. For example, it would be possible to select the most suitable collimator design for a given clinic without having to replace a whole treatment unit. In addition, in the event of equipment failures, a whole module may be exchanged for later repair, etc.

A fundamental module of a radiotherapy center is its radiotherapy treatment room. Since these treatment rooms have a lifetime of several decades, they will generally house many different treatment units during their lifetimes. For this reason, it is strongly desirable that standard room requirements should be formulated such that most treatment units can be accepted without shielding modifications.

Treatment Unit Designs

The Consultation considered further some of the more promising design concepts discussed above as well as improvements in the conventional radiotherapy machines, such as the classical linear accelerator and the ^{60}Co unit.

1. *The klystron/linac and high-frequency linear accelerator*
   Each of these offered the possibility of a compact, 6 MV, gantry-mounted accelerator. The klystron/linac and the integrated klystron/accelerator waveguide system do not require a particular resonance frequency. Higher-frequency accelerators of either the linac or microtron type would be less massive. Figure 5 illustrates the principle.

2. *Low-energy microtron ("Mini microtron")*
   A low-energy, in-line microtron design allows the possibility of a compact (30-40 cm diameter) 6 MV microton to be mounted in the gantry at the top of the radiation head. The small size of the accelerator can be achieved either by use of a higher frequency or by a higher energy gain per turn. It was considered that an integrated magnetron/cavity design might be advantageous. The microtron layout allows the field flattener to be placed in the fringing magnetic field thus reducing secondary electron emission. A photon beam spoiler may be employed for control of dose build-up for superficial targets. The accelerator could fit in a 80 cm or possibly even a 100 cm SAD gantry (Figure 6)

3. *Low-energy betatron ("Mini betatron")*
   In this design a small, 25 cm diameter, donut betatron mounted in the gantry at the top of the head provides a compact 6 MV machine. A high frequency (possibly 10 kHz) is required to provide adequate output. A dc bias can be used to double the energy gain (Figure 8)

4. *dc accelerators*

   A relatively compact, gantry-mounted accelerator can be achieved using dc accelerator principles. This machine was considered to be potentially very reliable. However, the 2-3 MeV maximum energy achievable was generally considered to be too low by most users. Heavy filtration of this beam would allow beam characteristics similar to a conventional 3 or 4 MV accelerator. The adequacy of the obtainable beam current may be a problem because of the heavy filtration. (Figure 11).

5. *Classical linacs (rf)*

   Commercial 4-6 MV linacs of compact design are widely available, though general concerns of cost and reliability were expressed (Figs. 4a and 4b).

6. *^{60}Co units*

   While ^{60}Co units have advantages of simplicity, relatively low capital and operating costs, low electrical, mechanical, and radiation maintenance costs, and insensitivity to environmental conditions, they provide depth dose characteristics that are not optimal for the full range of treatment requirements. Secondary disadvantages of commercial machines include excessively large penumbra, which require the use of penumbra trimmers, insufficient clearance between accessory holder and isocenter, and limited beam flatness. A new 100 cm SAD ^{60}Co gantry design was presented, which incorporated beam flattening using a copper flattener incorporated into the mirror, a 1 cm penumbra (P 80/20 at 10 cm) achieved using penumbra trimmers at 65 cm source-to-diaphragm distance, and a smaller diameter source, allowing adequate clearance and dose rate (Figure 12). The low isocenter height is achieved by tungsten shielding in the head. A 30 cm x 30 cm maximum field is flattened to 25 cm x 25 cm at 5 cm depth using a copper flattener with 80% transmission. The dose rate at isocenter (flattened) is 1.6 Gy/min. However such options would increase the cost of the unit, and the problem of replacing and disposing of the radioactive source, which is the critical factor in developing countries, remains.

Discussion of Design Criteria and Recommendations

Maintenance parts

It should be recognized that components of large, complicated equipment will, on occasion, fail to function properly. It is also recognized that unusual and sometimes even standard components are not readily available in developing countries. To overcome this problem in part, a selection of maintenance parts should be included in the initial price. In addition, a strong recommendation is given to include funds for periodic servicing in the initial price of the unit. It would also be advantageous to the users if the manufacturer/distributor of the equipment could establish a supply of maintenance parts at a regional location. Users on their side should arrange for local engineering support for maintenance. Such arrangements may result in significant cost savings, since many problems may be solved by telephone consultation even by local engineers with limited training. Users should also plan carefully the facility where the equipment is going to be used, to ensure reliability of operation and maintenance access.

Uninterrupted power supplies are strongly recommended in areas where large voltage fluctuations exist. Programmable logic controllers are widely used in industry and should be used where applicable in accelerators.

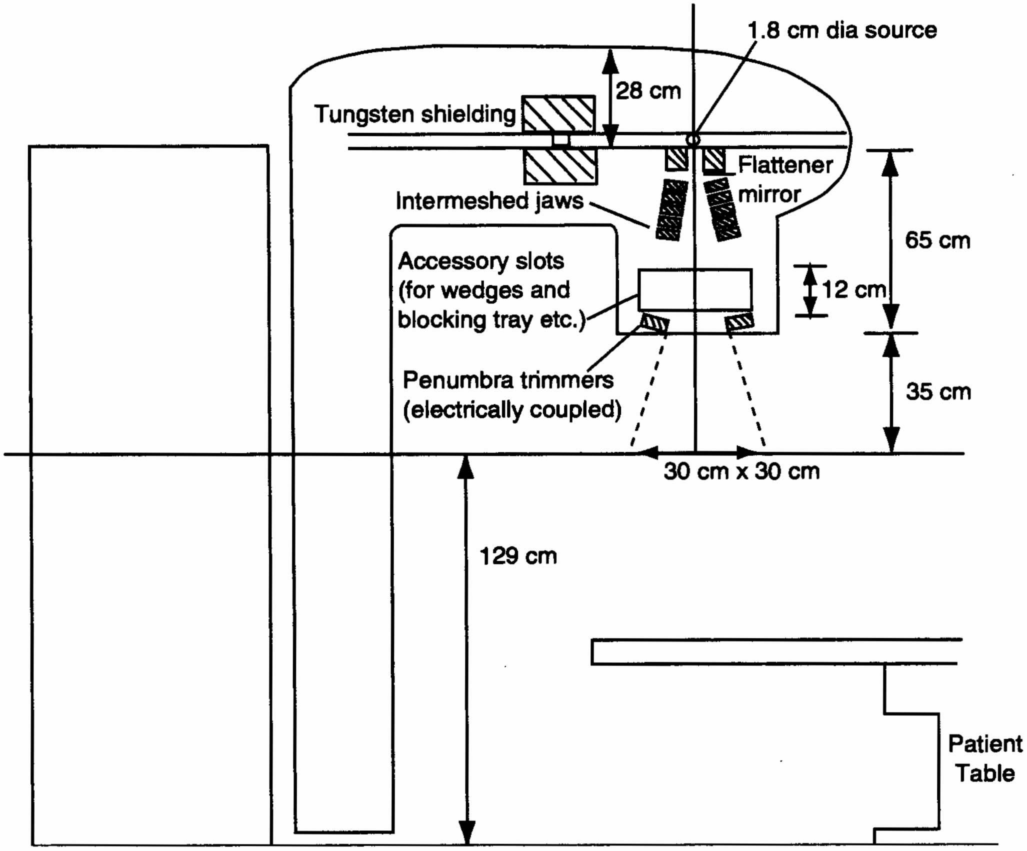

Figure 12. ^{60}Co. 100 cm SAD. (2.5 MV equivalent penetration).

Manufacturing costs

It was stated by representatives of the manufacturers at the Consultation that the manufacturing cost would be about the same for all of the accelerators discussed. In other words it was not established that one or more of the units could be manufactured at a substantial cost reduction relative to another. Small compact units would, however, have reduced costs in transport and installation.

The final price of a unit depends in part on the costs of research and development, manufacturing, distribution, warranties, maintenance parts, post-installation services, manufacturing location with respect to users location, and profit. In some cases, price reduction may be achieved if some major components could be manufactured locally. It is recognized that competition among manufacturers can contribute to price reduction. Ideally, the selling price of a new electrical machine should not exceed that of current top-of-the-line ^{60}Co units.

Proposals for Further Actions

It is now clear that with the increasing life span and changing life styles in developing countries, the incidence of cancer and the demand for radiation therapy services are increasing. This Consultation recommends that international organizations such as PAHO, WHO, IAEA and UNIDO investigate possible sources of funds to underwrite the development of lower-cost and more reliable alternatives to present electron accelerator designs. In view of the highly technical and frequently proprietary nature of the development efforts required to advance radiation therapy technology, the Consultation encourages the participation of the national research laboratories of the industrialized countries in this effort. The Consultation also recognizes the economic importance of supporting regional manufacturing initiatives in lesser-developed countries. This should be taken into account in evaluating industrial proposals. Such a program would open the attractive possibility of an international collaboration that would both stimulate the economies and raise the technical level in the developing countries, while improving their access to highly technical medical equipment. Regardless of the location where they are to be manufactured, new radiotherapy units must conform to international standards (ISO, IEC) to ensure the compatibility and the feasibility of global distribution.

The Consultation also encourages the international organizations to approach agencies such as the World Bank to investigate the possibility of obtaining partial financial support for block purchase of several units to be placed in developing countries. Such a multi-unit order should attract very competitive bids from the industry, resulting in substantial savings.

The Consultation also recommends that the international organizations initiate case studies in developing countries where units have been installed to determine what problems are typically encountered with current equipment in routine therapy and what obstacles must be overcome by the staff. The lessons learned from such a study would provide valuable input for the specification of future machines.

One of the most important goals of PAHO/WHO is to assure the equity of health services for all. In the area of radiotherapy this implies not only the availability of equipment, but that of trained personnel as well. To this end certified training facilities should be established in the developing countries. Regarding equipment, at least one or two modern megavoltage radiotherapy units should be made available for training purposes at each medical college and major medical institution of these countries. Regarding staff, the developing countries should establish training programs for the following:

- Radiation oncologists who must plan and oversee the delivery of adequate therapy treatments and provide patient follow-up.
- Physicists and dosimetrists who must assure proper calibration and dosimetry.
- Engineers who must perform equipment maintenance.
- Technical personnel who must carry out the radiation therapy treatment and fabricate patient accessories such as immobilization devices, and beam modifiers such as wedges and compensators.
- Auxiliary personnel who provide the support necessary to maintain a viable radiotherapy program.

It is only with such resources that these countries can develop a self-sustaining pool of skilled physicians, physicists, engineers, and technicians. The Consultation recommends that PAHO/WHO host a follow-up meeting to establish minimum training requirements in these specialties.

SESSION V: DISCUSSION AND GENERAL CONCURRENCE ON PRINCIPLES OF ADVISORY GROUP CONSULTATION REPORT

Moderator: U. Madhvanath
Discussion Leader: J. Stovall
Secretary: K. Brown

The report was discussed and adopted by the participants.

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APPENDIX 1

ADVISORY GROUP CONSULTATION ON THE DESIGN FOR MEGAVOLTAGE X-RAY MACHINES FOR CANCER TREATMENT IN DEVELOPING COUNTRIES

6-10 December 1993
Washington, D.C.

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