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ABSTRACT

The Patient Treatment Room at the Bevalac is now in full operation. In the design of this facility, emphasis has been placed on creating an atmosphere appropriate to a clinical facility; the usual features of an irradiation cave have been hidden behind carpets, curtains and paint. Patient positioning is done with a Philips Ram-style couch, with additional fixtures to accommodate a patient in the seated or standing, as well as the supine, position. Dosimetry apparatus, collimators, ion chambers and the beam flattening system used to produce the highly uniform 20 cm diameter therapy field are described.

INTRODUCTION

The potentially great advantages to using high LET (Linear Energy Transfer) radiation for the treatment of cancer have been well demonstrated in clinical studies with neutrons, negative pi mesons and heavy ions at several institutions around the world.[1] Studies are underway to explore these possibilities and develop appropriate techniques for optimum utilization of these treatment modalities.

This paper will discuss the facilities developed at LBL for patient treatment with heavy ion beams from the Bevalac.

Heavy ions offer two distinct advantages over photons: physical dose distribution and enhanced biological effectiveness. The sharpness of the characteristic heavy-ion range-ionization curve, called the Bragg curve (sharp peak in Figure 4) allows substantial sparing of normal tissue, both on the way into the tumor as well as in a very low exit dose beyond the tumor. The rigidity of heavy ion beams also means that the lateral edges of the irradiation field will be very sharp, at most a few mm wide. The utilization of these physical characteristics will be discussed below, under Beam Delivery. The biological advantages stem from the high ionization density at the end of the particle range (Bragg peak) which causes more permanent cell damage (less repair can occur) and so is more lethal to the tissue in which it stops. The lower ionization density along the entrance path is less damaging, and so more sparing of normal tissue.

These properties have been extensively studied at the Bevalac over the last four years with cell and animal radiobiology using beams of C, Ne and Ar.[2] The understanding gained from these studies has launched a full program of treatment of human cancers.

TREATMENT FACILITY

The facility layout is shown schematically in Figure 1. In addition to the treatment room, there is a staging area for physicians, physicists and technicians, an exam room, changing and waiting areas. Since a full patient reception and processing center is located in another nearby building, the patient waiting areas at the Bevalac are relatively modest.

Full control of all phases of the treatment, positioning, dosimetry, beam monitoring and control is done through the PDP 11/45 system in the Biomed control room where a full-time operator is in constant communication with the treatment room and the technician's control station.

The treatment room itself is designed to appear like a clinical area. Carpets, curtains and paint hide the usual features of the experimental caves. The curtain through which the beam passes to reach the patient (Figure 2) conceals much of the dosimetry and beam preparation hardware. The final range modulator (water column), ion chambers and collimators are set on the optical rails which are aligned with high accuracy (±0.2 mm) along the beam axis and can translate along this axis a total distance of 2 meters. The drive mechanism is below floor level.

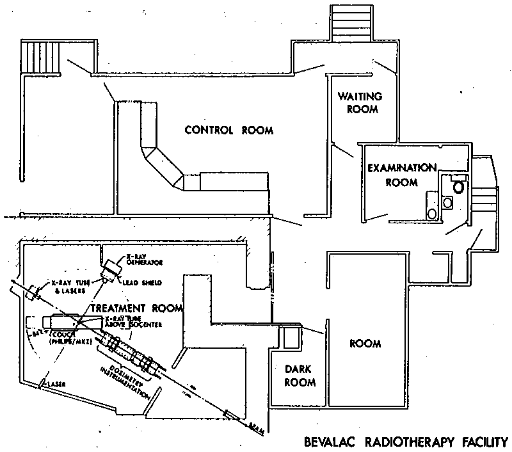

Fig. 1. Schematic layout of the Radiotherapy facility showing the treatment room, and ancillary areas. The area marked "room" houses the technician's control station, viewing boxes and a discussion area for physicians and physicists.

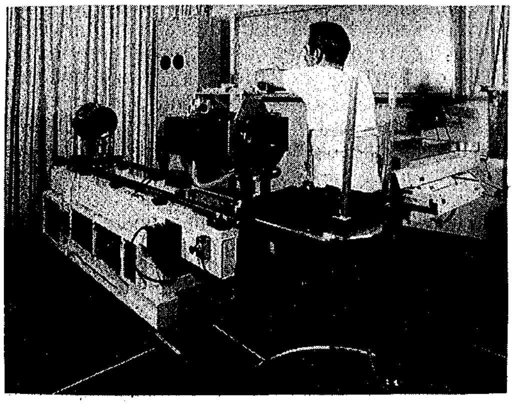

Fig. 2. Treatment room showing chair attachment to the Philips positioner. Beam comes through the curtain and passes through dosimetry apparatus before reaching the patient. Shown on the optical rails are an ion chamber, two collimators and the range-modulating water column.

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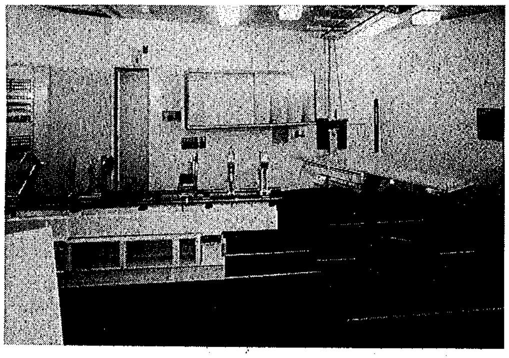

Fig. 3. Treatment room showing table-top assembly supplied with the Philips positioner.

To compensate for the lack of flexibility in beam delivery orientation (we must treat with a static horizontal beam) a very versatile patient positioning assembly has been installed. This unit, a Philips Mark I Ram-style positioner,[3] has four fully motorized motions, whose coordinates can be read and controlled by computer. It was supplied with a removable table top (Figure 3). At LBL we have fabricated a chair (Figure 2) and a platform for seated and standing treatment modes.

Patient localization with respect to the beam axis is performed using five cross-hair lasers, two installed at lateral locations, one directly on the beam axis and one overhead. All the laser beams are adjusted to pass directly through isocenter. X ray tubes are also located along the beam axis, and at lateral and overhead positions.

BEAM DELIVERY

The basic tasks in delivering heavy ion radiation to the tumor site are to adjust the beam range so that particles stop at all points within the tumor, and to spread the beam out so that all areas of the tumor receive the same dose.

The basic range-energy curve (Bragg curve) is shown as the solid line in Figure 4. Typically, the width of this curve is measured as less than 1 mm. To spread out this peak, the beam is passed through a device known as a Ridge Filter.[4,5] It consists of a brass plate with a precisely machined spiral groove. The exact shape and depth of the groove determine the form of the spread-out Bragg curve. The dotted curve in Figure 4 is a typical example of a modified Bragg curve. The shape of the desired Bragg curve is determined from the results of biology experiments, since one is searching for equal biological effectiveness over the entire range of the spread-out Bragg peak. This "iso-effect" criterion is the reason that the dotted curve in Figure 4 is not flat.

A whole family of ridge filters has been fabricated to cover the full range of treatment situations, namely different degrees of beam spread for each of a number of beam particles and energies.

To facilitate biology and dosimetry studies, certain fixed beam energies were selected. Fine adjustments in the beam range, to assure that it stops in the tumor, are performed with a computer-controlled water column.[4,5] This instrument consists of two lucite plates driven by precision lead screws. As they move apart, water is drawn into the area between them, forming a carefully controlled variable degrader. The thickness of water can be varied in 0.1 mm steps from 0 to 30 cm. The water column can be seen on the optical rails in front of the patient in Figure 2.

The lateral spreading of the beam into a uniform field is done with the scattering-foil occluding-ring system used at Harvard[6] and at the LBL 184" cyclotron[7] (see Figure 5). The beam is scattered into a symmetric Gaussian distribution by the first scattering foil (in our case typically 0.6 cm of lead) located 10 meters from the patient. After travelling 4 meters, this Gaussian beam has a half-width of about 4 cm. At this point a set of concentric brass rings blocks out certain portions of the distribution. A ridge filter, along with an additional 4 mm of brass, is attached to these rings to form the second scatterer, acting as a diffuser to give angular spread to the beam. As the beam moves towards the patient, the blocked-out regions are filled in by the scattered beam, and at the patient site the total beam profile is completely flat with an intensity variation of no more than ±2% over a 20 cm diameter field. Furthermore, 40% of the original beam intensity lies within this flat region, providing excellent utilization of the available beam.

As one might anticipate, the setup and tuning of this system to achieve the quoted flatness is a sensitive procedure. Small misalignments of the beam on the occluding rings can cause substantial skewing of the intensity profile.[6] To help in the tuning and beam-flatness verification a sophisticated proportional chamber called MEDUSA was built. This instrument, described in detail in the following paper,[8] is a

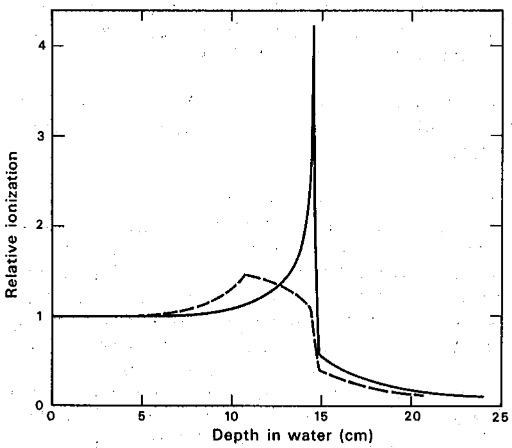

Fig. 4. Range-energy curves measured for a typical heavy ion beam at the Bevalac; the unmodified curve (solid line) showing characteristically sharp stopping point, and the spread-out curve (dashed line) resulting from passage through the ridge filter. The ionization beyond the stopping point in both curves is due to nuclear projectile fragments, which have longer ranges than the primary beam.

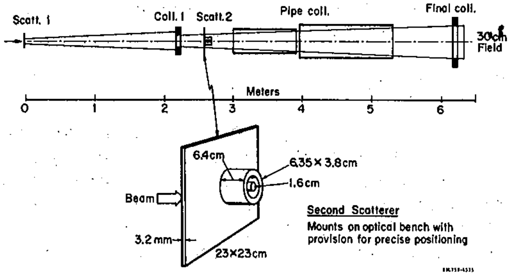

Fig. 5. Beam flattening system used at the LBL 184" cyclotron and the Bevalac. Occluding rings block out portions of the Gaussian-shaped beam. Scattering plus drift length combine to produce a very uniform distribution at the site of the patient.

multi-plane multi-wire chamber which uses CT algorithms to reconstruct its data into a 64 x 64 picture of the beam profile passing through the chamber. The high precision and fast reconstruction speed make this an ideal device for tuning and verification of the treatment field.

DOSIMETRY AND CONTROL

Dosimetry is performed with three ion chambers,[4,5] one located upstream of the occluding rings, the other two close to the patient. They are calibrated daily for each patient setup with an EG&G standardized ion chamber. One of the two downstream chambers is read independently of the computer by a count-down scaler, and serves to terminate the treatment should a computer malfunction occur.

The control software (a program called HIRAD) on the PDP 11/45 system monitors and provides archival storage for all of the treatment parameters, including ion chambers, beam intensity, water column setting, ridge filter rotation, patient couch coordinates, etc. It also controls the startup and termination of treatment, removing the beam plug to bring beam into the treatment area. When the desired dose is achieved, a signal is sent which aborts the Bevatron spill (within 1 msec) while the beam plug is inserted back into the line. Elaborate safety provisions have been implemented to provide redundancy and protection against system failures. An operator constantly monitors the computer display during treatment and can activate emergency shut-offs should he detect any abnormality. This crash-off capability is also available at the radiological technician's station.

RUNNING EXPERIENCE

The patient treatment program has now been in operation six months. We have treated primarily with carbon beams at 400 MeV/amu, but have also performed treatments with neon and argon beams. Typical Bevalac carbon beams are quite intense, up to 2 to 3 x 10^{10} particles per spill, which translates into a dose rate of over 400 rads per minute over the entire 20 cm diameter treatment field. This rate is such that a typical treatment is completed in much less than one minute.

One of the reasons for concentrating on carbon ions has been the availability of steadily improved beam intensities from the local 20 MeV injector. The latest output is 4 x 10^9 particles per pulse at the patient (almost 100 rads per minute), adequate for most treatments. This redundancy of injectors adds substantially to the beam-delivery reliability.

Machine-time scheduling to accommodate the radiotherapy program has had a substantial impact on the conduct of nuclear science experiments. The machine is reserved for therapy four day-shifts each week, leaving a block of 11 contiguous shifts each weekend for a long nuclear science run. The evening week-day shifts are used for machine studies, radiobiology or nuclear science. Two shifts for maintenance are taken from the nuclear science period on alternate weeks. This schedule permits patients to receive four treatments per week; a full course of treatments will ultimately consist of twenty fractions.

At present three treatments per day are conducted, but as experience is gained and procedures improved a full patient load of seven to ten per day is anticipated.

FUTURE PLANS

We anticipate substantial efforts in the future to develop and improve beam delivery systems. The great alignment accuracy required for the occluding-ring flattening system can be avoided by using a beam wobbler. This device consists of a rotating dipole field (provided by a stationary sextupole magnet driven with 3 phase 60 Hz AC power) which sweeps the beam in a circular pattern at the patient. Field size is provided by appropriate settings of magnet current and the thickness of a scattering foil located at the magnet.

Further in the future is a full three dimensional beam scanning system[9] capable of sweeping a tightly-focused beam across the desired treatment volume. This scanning system will be controlled by a computer which receives input directly from treatment-planning and CT scanner computers, thus providing the radiotherapist with a completely automated path from diagnostics to treatment. We already have constructed a prototype scanning magnet and power supply, and will be testing it shortly.

In summary, we view our radiotherapy facility as a prototype, in which the developments, techniques and experience gained in our day-to-day operation will provide invaluable insights into how to bring heavy-ion therapy most effectively into the hospital environment.

ACKNOWLEDGMENTS

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