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MEDICAL 6 MeV LINEAR ACCELERATOR MADE IN JAPAN

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A 6 MeV medical linear accelerator manufactured by the Mitsubishi Heavy Industries, Ltd., has been installed in the Aichi Cancer Center Hospital. This is the first unit of this type made in Japan. This paper gives a brief description of the unit, reports the results of a series of tests for radiation and mechanical accuracy, and summarizes the one year history of calibration and stability. One of the most striking characteristic is a mechanism that deflects the electron beam, coming out of the acceleration tube at 180 degrees and using two steps deflection magnet system. The maximum X-ray output was 465 R/min at one meter from the target with the actual maximum energy of 5.75 MeV. The unit was used for clinical radiotherapy for the past year, and treatment was only interrupted one day because of mechanical trouble.

Within the past few years, three configurations of linear accelerators designed specifically for medical applications have been developed and produced in Japan. Although two of these units were made with introduction of the technology in the foreign countries, the unit discussed in this paper was developed, independent of foreign technical contact or help, by Mitsubishi Heavy Industries, Ltd. under the medical guidance of Dr. S. Takahashi, consultant radiologist of Aichi Cancer Center.

In December 1966, the first model of the medical linear accelerator was installed in the Aichi Cancer Center Hospital. Since then, other units have been supplied to various hospitals in Japan; however, this paper primarily reports the results of developmental tests performed on the first model, on performance tests performed at the Aichi Cancer Center between December 1966 and March 1967, and on operating and reliability characteristics observed during the first year of clinical application for treatments (March 1967–March 1968).

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STRUCTURE OF THE MACHINE

The unit consists of the main body, a control panel, an electron power supply, a treatment table, and a control pendant. The main body is further divided into two parts: the rotating gantry and the fixed portion. The rotating gantry contains an electron acceleration system, a magnetic system, an X-ray head, and a vacuum control system. The fixed portion contains a cooling mechanism, a main body driver, and portion of the electric power supply. Picture of the linear acceleration is shown in Fig. 1. Diagram of the mechanical layout is shown in Fig. 2.

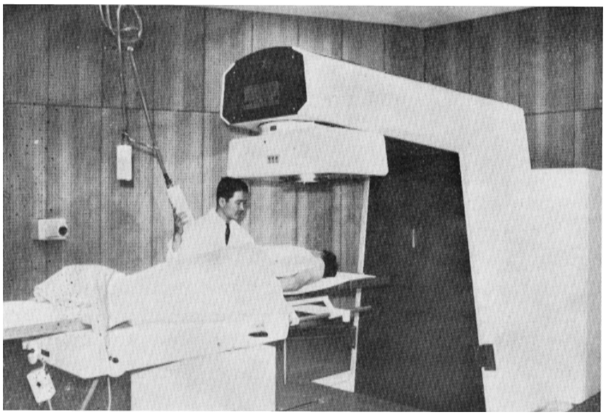


FIG. 1. A view of Mitsubishi medical linear accelerator

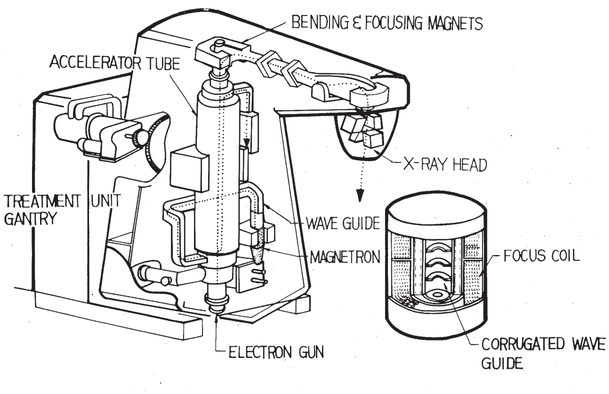


FIG. 2. Diagram of the mechanical arrangement of the linear accelerator

Electrons are accelerated with an energy up to 6 MeV by the electron acceleration system which consists of the electronic gun, acceleration tube, magnetron, wave guide circuit, etc. About 60% of all the electron in the beam attain an energy level within 6 MeV±0.1 MeV, when measured near the exit of the acceleration tube. As the electron beam exits from the acceleration tube it is deflected 90° by the first deflection magnet. After passing through the steering coil and beam ampere meter, the electron beam is further deflected 90° by the main and fine deflection magnets. Thus after experiencing a total deflection of 180°, the electron beam is converted into X-ray by striking an X-ray target. X-rays then pass through the ion chambers, the primary collimators, multileaf collimators, and then reach the patient.

Developmental tests revealed that three subsystem controls required regulation to insure stable radiation output dose rates. First, the cooling system for the accelerator tube is regulated to control the tube temperature within ranges of 40°C±0.2°C. Second, an automatic frequency control system (AFC) maintains the magnetron frequency at 3000 Mc/s±40 Kc/s. Third, the automatic dose-rate control system regulates the pulse repetition frequency of the pulse generator.

Details of the mechanical structure of this machine are described elsewhere[3) 4)].

RESULTS OF TESTS

1) *Size of X-ray Focus:* The X-ray focus was measured by three methods; the Farady cup method, the pin-hole photograph method, and the wire penetrameter method.

In the Farady cup method, a small round hole was set at the site of the X-ray focus. A Faraday cup placed behind the small hole was used to measure the electric current of the electron beam passing through the hole. Measurements were made using several different size holes. When a hole of 2 mm in diameter was used, the electric current efficiency was 70% and did not increase

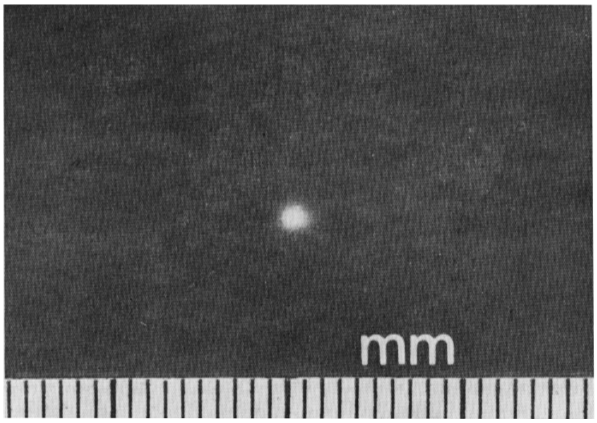


FIG. 3. Pin-hole radiograph of the X-ray focal spot

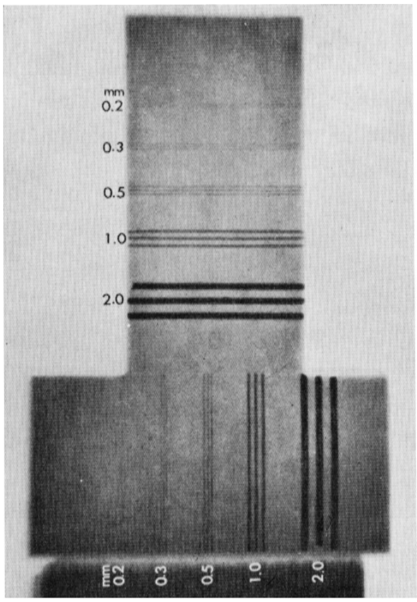


FIG. 4. Radiograph of the wire penetrameters

when the diameter was increased to 2 mm or more. Therefore, the diameter of convergent electron beam was estimated to be under 2 mm.

In the pin-hole method, a lead plate with a pin-hole of 0.5 mm in diameter was placed and set at a point 60 cm from the target and 60 cm from the film. The pin-hole picture obtained is illustrated in Fig. 3. This method of measuring the sharpness of focus was not considered successful because the lead plate could not be made thin enough to prevent edge dispersion. From the results obtained, however, the spot was radiographed to be a little more than 1 mm.

In the wire penetrameter method, a resolving power is measured and the size of the focus is calculated[5].

Three tungsten wires of 2.0, 1.0, 0.5, 0.3, and 0.2 mm in diameter respectively were arranged parallel to each other with the same interspace as the diameter of wire and fixed in the surface of an acrylite plate. This is called as a wire penetrameter which is recommended by the ICRU[6] for measuring the resolving power of radiographic equipment.

In this method, a equation has been found by Komiyama[5].

$$n_1 = m\frac{b}{a-b}$$

Where "a" is the diameter of the focal size, "b" is the diameter of wire, "m" is the focus-to-wire distance and "n_1" is the wire-to-film distance when the penumbras of the individual wires are adjacent with no spacing and no overlapping. This condition was satisfactory for $m=77$ cm when n_1 was fixed at 33 cm and a penetrameter with a 0.3 mm wire ($b=0.3$) was utilized. This resulted in a focus diameter calculated to be 0.9 mm in diameter.

As a result of the above three experiments, the X-ray focal size was estimated to be smaller than 2 mm in diameter.

2) *X-ray Output:* This machine was designed for maximum X-ray emission and stability at an electron energy level of 6 MeV. Therefore, in this paper the performance reported is that achieved with a 6 MeV (nominative) energy level unless otherwise noted. The X-ray dose was monitored by a parallel plate type dose-rate meter set near the radiation mouth. The monitor dosimeter consisted of two chambers, the upper and the lower. Each chamber was independently monitored by separate dose-rate meters on the control panel. The total dose was measured by integrating the measured rate of the upper ionization chamber.

The relationship between the pulse repetition and X-ray dose rate is shown in Fig. 5. This was measured by the Radocon dosimeter Model 575 # 607 with an acrylite cap under the conditions of 1 m in FSD and 30×30 cm of radiation field size.

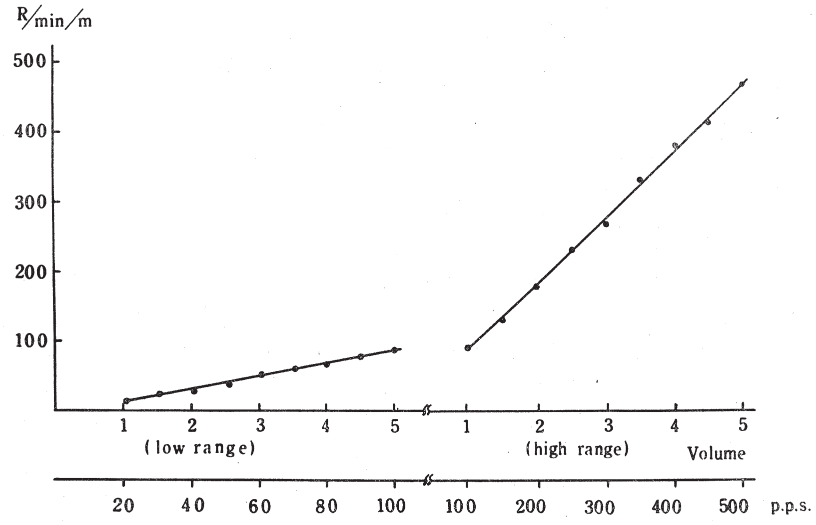


FIG. 5. Pulse repetition rate and radiation dose-rate. Two-phase of line was produced by two-step change of the volume.

These test results show the radiation dose to be lineally proportional to the pulse repetition rate. The repetition rate is controlled by a range switch and a continuously variable potentiometer is located on the control panel. The switch selects a high or a low repetition rate range, and the potentiometer provides for a continuous linear setting over the selected range as shown in Fig. 5. In this test, the maximum repetition rate was 500 pps, and at that time 465 R/min were obtained 1 m from the target. This value is the maximum output X-ray dose of this unit. The accuracy of the monitoring dosimeter is shown in Fig. 6 from the results of calibrating this unit against the Radocon # 607 dosimeter.

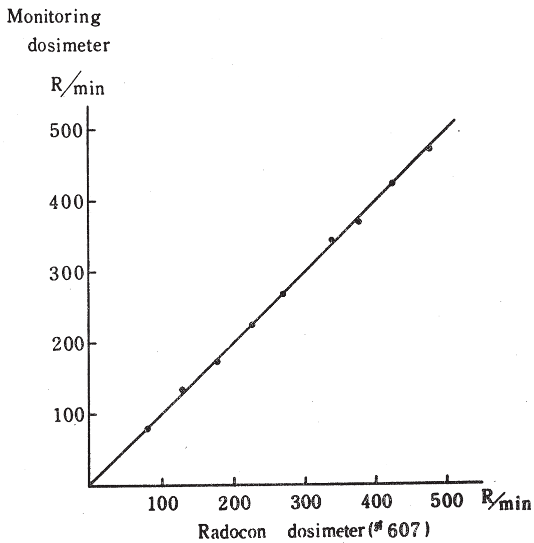


FIG. 6. Correspondence of the monitor dosimeter with the Radocon dosimeter

3) *Output Stability:* The dose-rate fluctuations were measured during long periods of irradiation. Under the conditions of 1 m in FSD and 30×30 cm in field size, a Radocon # 607 with the acrylite cap was placed at the isocenter (rotation center of the machine). The output from the Radocon dosimeter was introduced into the Yokogawa Recorder YEW-TER-11. The results of twenty minutes of recording is shown in Fig. 7. Near the points of 9 and 12 minutes, there were several noise spikes caused by an electric discharge in the magnetron. If these noise spikes are disregarded, the dose-rate fluctuation falls within a range of $\pm 0.8\%$. This test was repeated 20 times and the dose-rate fluctuation was always under $\pm 1.0\%$.

Next, the initial transitional dose-rate was measured. The test methods were the same as described above with the results shown in Fig. 8. The time required from the instant the unit was turned on until the unit delivered a full output dose-rate was 1.1 seconds, which is of little clinical significance. The dose-rate stability was measured while rotating the movable section of the unit.

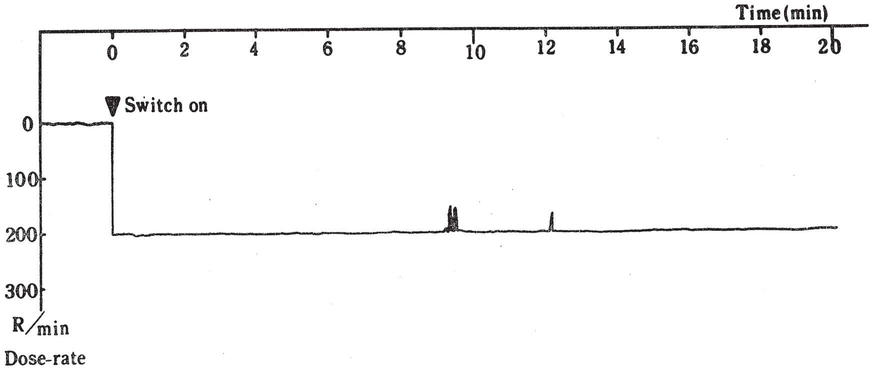


FIG. 7. Stability record of X-rays

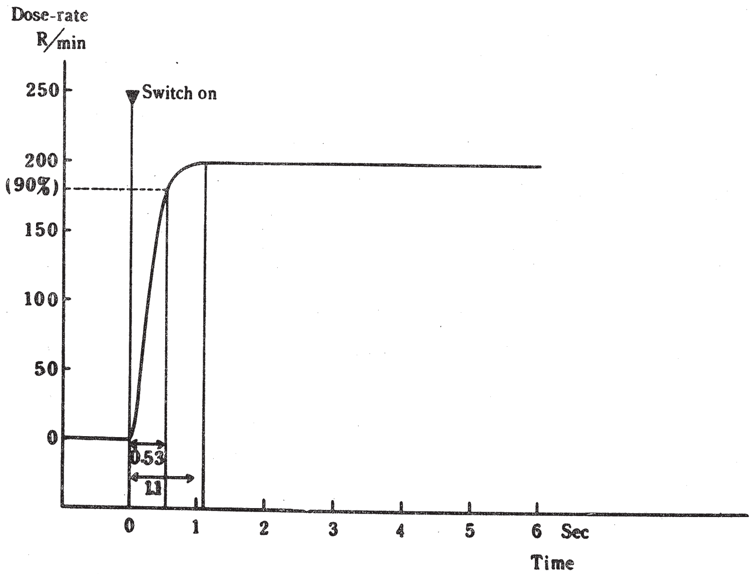


FIG. 8. Initial transitional characteristics of dose-rate

At the center of the radiation field of 30 × 30 cm in size at 1 m from the target, the Radocon #607 dosimeter with the acrylite cap was fixed, and the dose-rate was continuously recorded by the Yokogawa Recorder type YEW-PRO-12. The rotating speed of the machine body was maintained constant at 1.0 rpm throughout this experiment. As shown in Fig. 9, the variation ranges were 7.5 R/min for clockwise rotations and 6.2 R/min for counterclockwise rotations while delivery is a nominal dose-rate of 200 R/min. These variations correspond to ±1.9% and ±1.6% respectively.

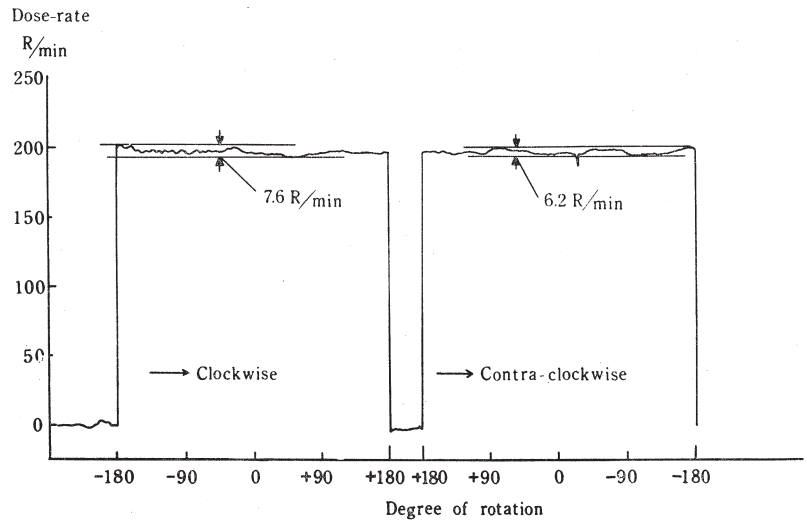
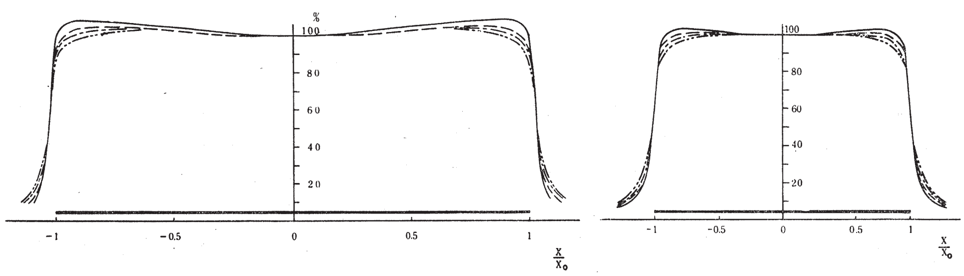


FIG. 9. Stability of X-ray dose-rate during rotation irradiation

4) *Flatness of Dose-Distribution:* A study was conducted to determine the flatness of the dose-distribution at various depth of the subject. Since the dose distribution is greatly influenced by the amplitude of the current in the main and fine deflection magnets, this test was conducted while carefully controlling the magnet current. Dose distributions of X-rays at depths of 1.2, 5, 10, and 15 cm in water were measured and recorded by the Toshiba automatic iso-dose plotter in 30×30 cm and 15×15 cm field size. The results of the tests are shown in Fig. 10 (a) and (b). The dose distribution at a depth of 10 cm of water was almost flattened and suitable for practical use. These flatness measurements were performed in the perpendicular plane of the center of the radiation field. Fig. 11 shows the dose distribution in a plane 10 cm from the field center. In this figure the measured planes are shown by the symbols A, B, and C.



(a) (b)
FIG. 10. Flatness of dose distribution in water
(a) 30×30 cm field size (b) 15×15 cm field size

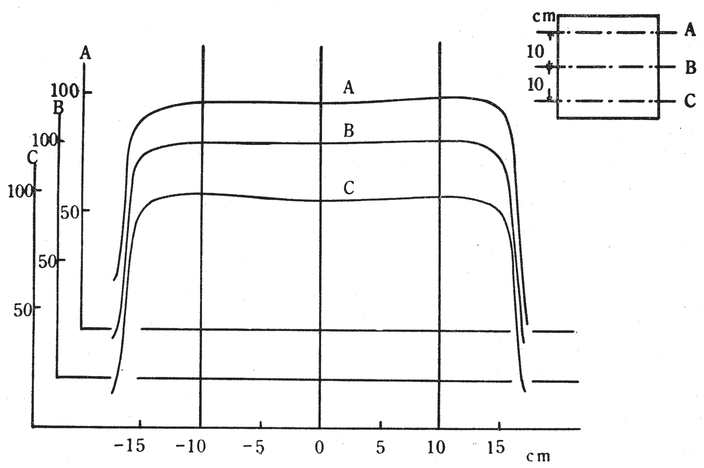


FIG. 11. Flatness of X-ray dose distribution in the different planes within the radiation field
A, B, and C represent dosimetried planes. See text.

Depth dose curves and isodose curves for an energy setting of 6 MeV are illustrated in Fig. 12 and 13. These data were measured by the Toshiba thimble type dosimeter.

5) *Electron Beam:* The primary design characteristic of this element is the energy control range which can be adjusted from 4 to 8 MeV. However, whenever energy of electron beam was changed for practical use, electric current of the bombarder and deflection magnets should be regulated, and hence flatness of dose distribution also should be checked. Therefore, we used

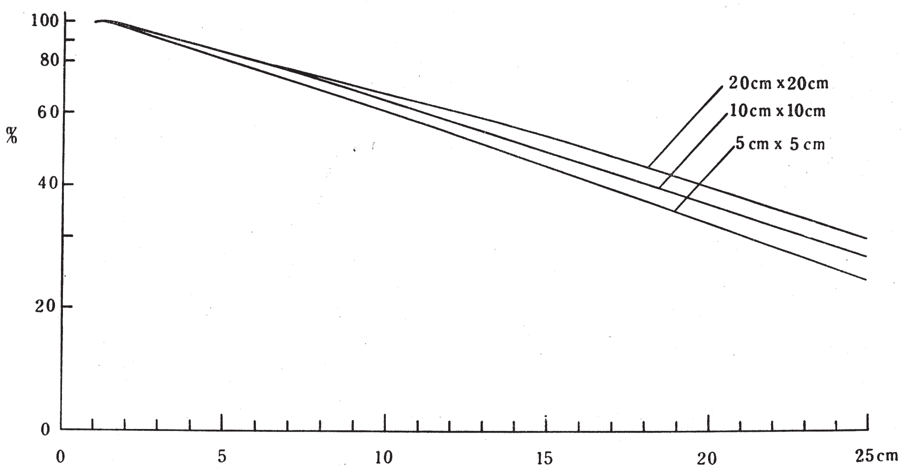
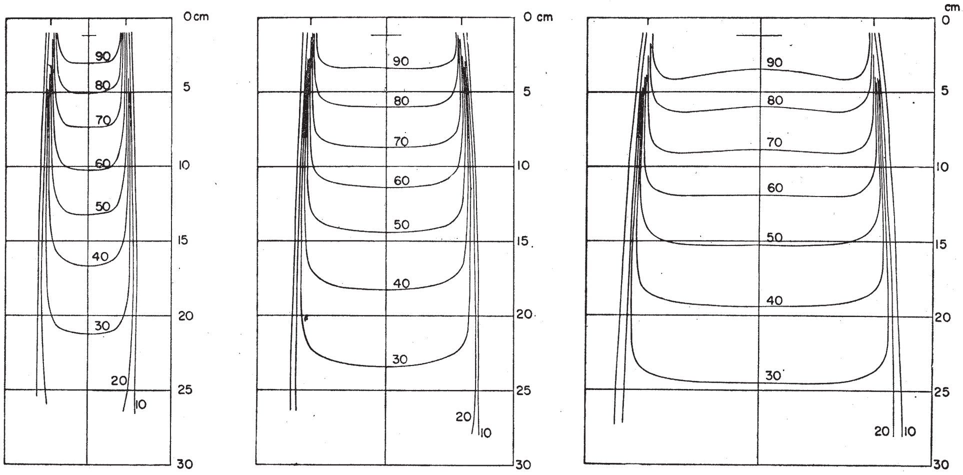


FIG. 12. Depth dose curves of 6 MeV X-rays in different field size



(a) (b) (c)

FIG. 13. Relative dose distribution of 6 MeV X-rays
(a) 5×5 cm (b) 10×10 cm (c) 15×15 cm

usually one fixed energy of nominative 6 MeV, in which the operating conditions were most stable. Electron beam was taken out by switching of deflection current value. Depth dose curve was obtained in the conditions of 5×5 cm in the field size and 20 pps in pulse repetition rate as shown in Fig. 14. The extrapolated range of electron beam in this figure corresponded to 5.75 MeV. We call this value as a so called 6 MeV electron beam of this unit.

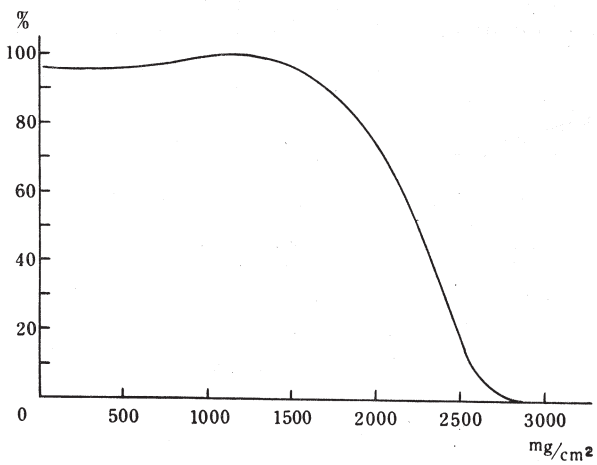


FIG. 14. Depth dose curve of 6 MeV electron beam in polystylene phantom

Extrapolated range corresponds to an energy level of 5.75 MeV.

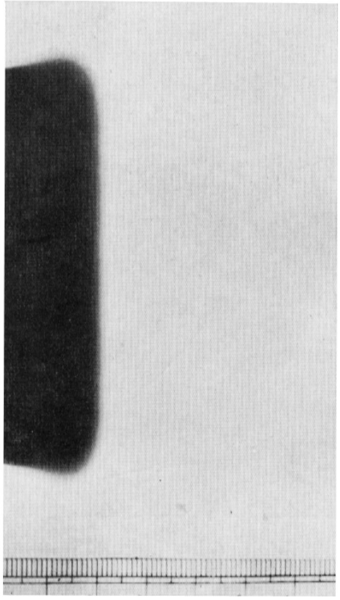


FIG. 15. Dose distribution of 6 MeV electron beam (Film method)

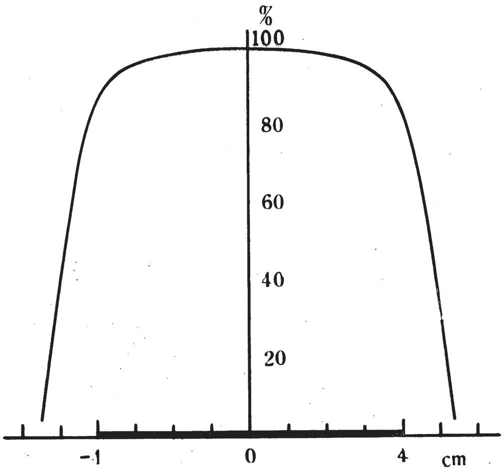


FIG. 16. Flatness of dose distribution of 6 MeV electron beam

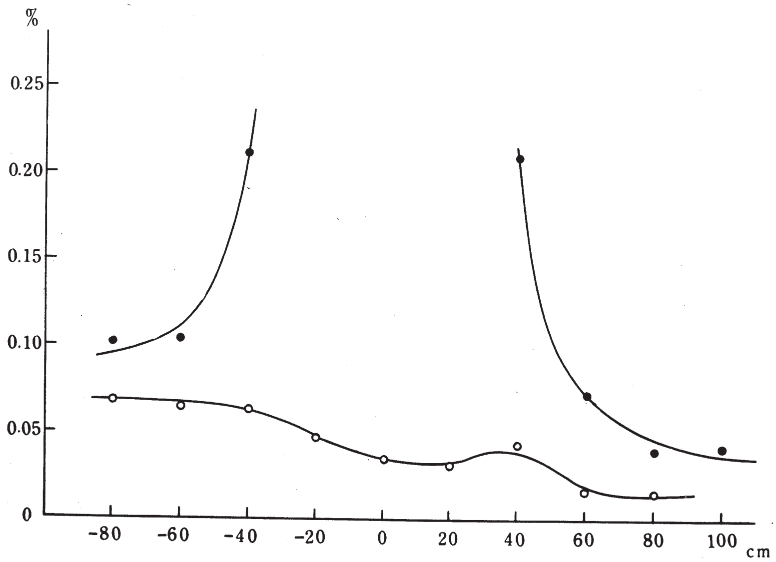


FIG. 17. Leakage radiations in the plane of direction to beam

Black dots: Peripheral radiation dose distribution in the radiation field of 30×30 cm in size.

White dots: Radiation dose at the isocenter passed through the completely shut collimator.

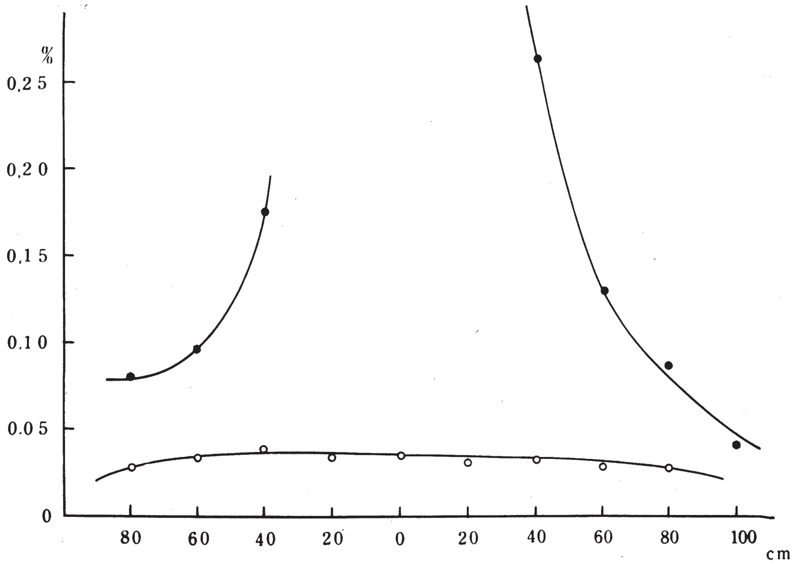


FIG. 18. Leakage radiations in the plane rectangularly faced to electron beam acceleration
The black and white dots represent the same as in Fig. 17.

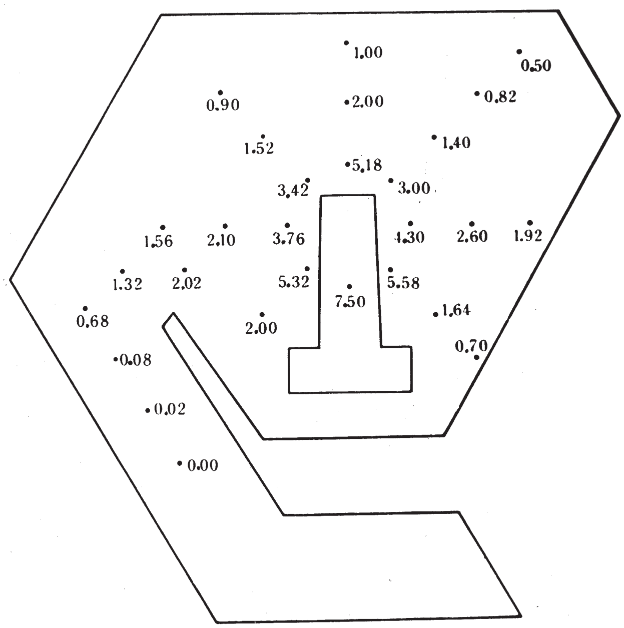


FIG. 19. Distribution of scattered radiations in the treatment room measured at the level of 1 m from the floor

Relative dose distribution in this energy are shown in Fig. 15 and 16.

6) *Leakage Radiations:* The dose distribution surrounding the radiation field of 30×30 cm and the radiation dose at the isocenter through the shut collimator were measured. The pulse repetition was adjusted to deliver an X-ray intensity of 350 R/min at 1 m. The Victreen R-meter was used. Results are shown in Fig. 17 and 18. Next, scattered radiations were measured in the treatment room under the operating conditions of a 30×30 cm field and a 200 R/min dose-rate at 1 m. The dose-rate meter used was the Radocon #608. Results are shown in Fig. 19.

7) *Mechanical Accuracy:* The mechanical accuracy of the iso-center and the speed characteristics of the rotating gantry were tested. An X-ray film in a black envelope was placed on the iso-center with the X-ray beam parallel with the film plane.

The film was exposed through a small slit for each 30 degrees or gantry rotation. As is seen in Fig. 20, no detectable variations of the iso-center were observed. This test was done once a month for one year. The observed variations were distributed within the ranges of ± 1 mm.

In this unit, there is a speedometer and speed-regulating potentiometer on the control panel. First the speedometer was calibrated by measuring both the clockwise and counterclockwise time of rotation with a stopwatch. These

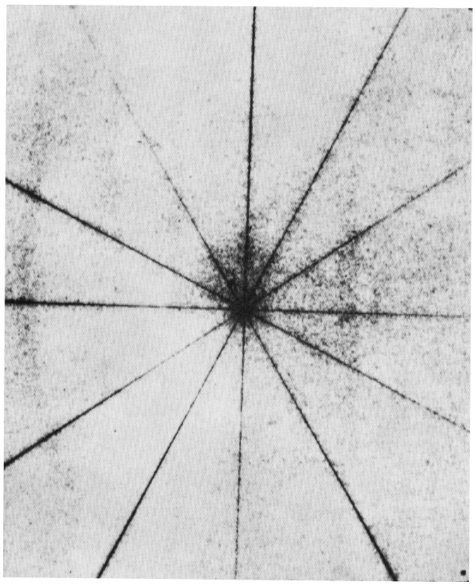


FIG. 20. Mechanical accuracy of the isocenter. Narrow beams emitted from various directions during rotation of the unit.

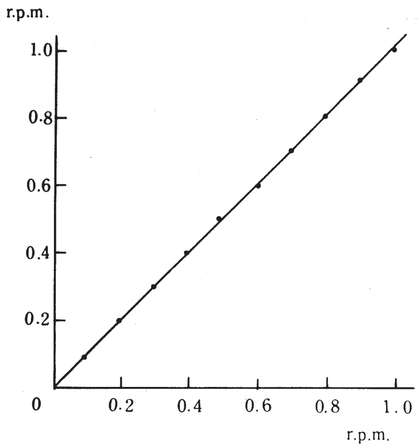


FIG. 21. Reliability of speedometer.
Ordinate: actual speed measured.
Abscissa: indication of speedometer.

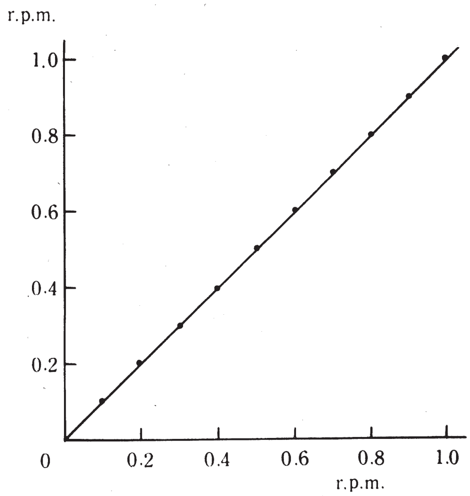


FIG. 22. Reliability of speed regulating control.
Ordinate: actual speed measured.
Abscissa: indication of speed regulating control.

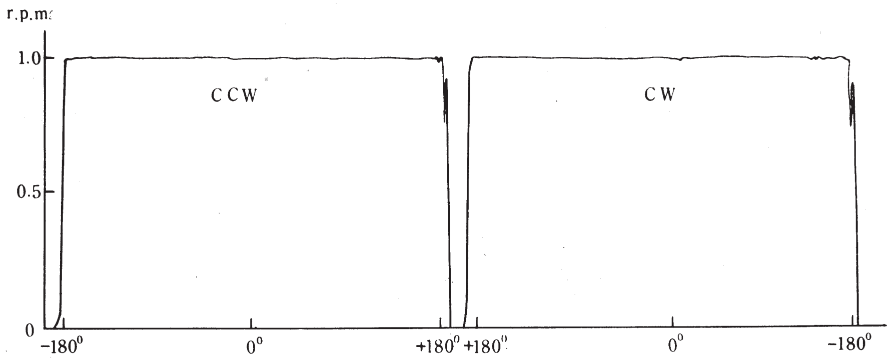


FIG. 23. Stability of rotation speed

measurements were compared with the unit speedometer, and the results are shown in Fig. 21 by the comparative calibration curve. This curve indicates the speedometer to be as accurate as the stop watch method. In Fig. 22 the calibration curve of the speed adjustment control shows the control setting indicator to be as accurate as the measuring device. Fig. 23 is a record of speed uniformity in rotation of 1 rpm by the Yokogawa Recorder YEW-TER-11. The output of speed was taken from the tachogenerator.

8) *Running Test:* Variation of X-ray dose-rate and vacuum level were recorded for a two day irradiation test period. Initially the X-ray dose was set

to 208 R/min at 1 m. The Radocon #607 dosimeter was connected with the Yokogawa Recorder and the dose rate was recorded for two days. The dose-rate varied over a range of 206 to 210 R/min. The vacuum level monitored and observed to fluctuate between 5 and 8.5×10^{-7} mmHg.

9) *Comparison with Design Requirements (Target Values):* This linear accelerator was designed and developed under the medical guidance of Dr. S. Takahashi, who established the design parameters or target values for the unit before the target mechanical performances and efficiencies developmental program was initiated. Table 1 lists these target values and compares them with the test results obtained from the completed unit. In most cases the measured results were somewhat better than the target values.

TABLE 1. Comparison of Test Results with Target Values

Parameters	Target values	Measured results
1. Size of X-ray focus	Under 2 mmφ	Under 2 mmφ (Farady cup method)
2. Reliability of monitor dosimeter	Within ±5%	Within ±3%
3. X-ray output	350 R/min/m	465 R/min/m (500 pps)
4. Output stability	Within ±3%	±1%
5. Time required full output dose-rate	Under 5 sec	1.1 sec
6. Output stability during rotation of the head	Within ±3%	±1.9%
7. Flatness of dose-distribution	Within ±3%	±2.5%
8. Maximum energy of electron beam	6 MeV	5.75 MeV
9. Leakage radiation	Under 0.1%	0.08%
10. Mechanical accuracy of iso-centre	Within ±1 mm	±1 mm
11. Vacuum	10^{-6} mmHg	8.5×10^{-7} mmHg

RUNNING AND MAINTAINANCE

Tests of performances and efficiencies in this unit were finished on 20th March, 1967, and the machine has been used for clinical treatment since 25th March, 1967. The experience gained during the first full year of operation has shown that the following four points should be periodically checked and/or calibrated.

1) *Variation of Energy:* The direct measurement of the electron energy was impractical and probably of no clinical significance. Instead of the direct method, an alternate measurement of the dose at a depth of 10 and 15 cm in water was made. The results of these measurements made over a one year period are shown in Fig. 24. No significant variation was observed.

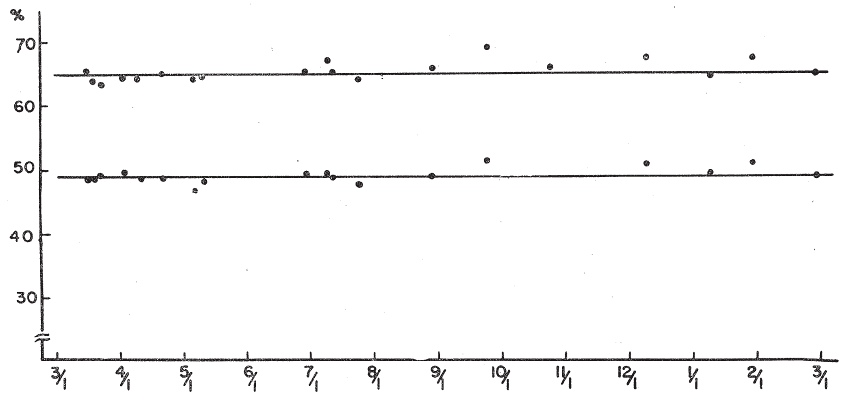


FIG. 24. Variation of percentage depth dose of X-rays

2) *Conversion Factor:* The calibration of the dose register should remain accurate with little variation in the conversion factor (the ratio of true radiation dose measured by the Victreen R-meter at the iso-center and the indication of the dose register on the control panel). In this unit, a drift or tendency to vary was present as seen in Fig. 25.

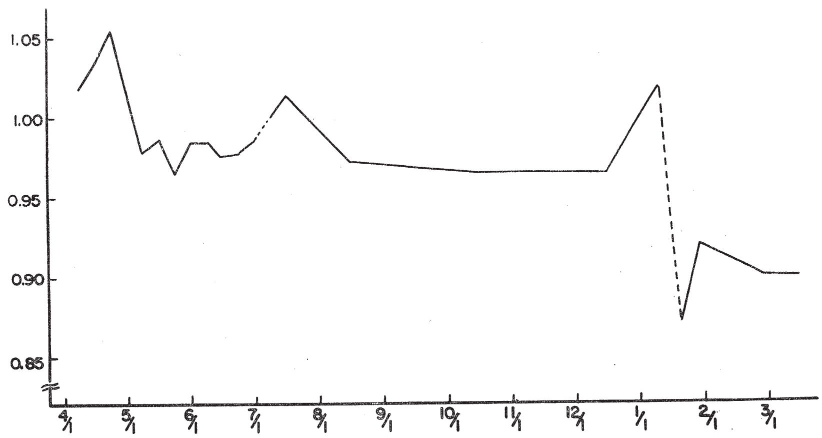


FIG. 25. Variation of conversion factor

3) *Flatness of Dose Distribution:* Dose distribution flatness is largely influenced by changes of current amplitude in the deflection magnets. During the one year test period, it was determined that the dose flatness should be checked once each day and this measurement was made with the Mitsubishi flatness monitor. The current in the deflection magnets was adjusted daily to maximize the flatness of the dose distribution. The required magnet current to maximize the flatness of the dose rate for the one year test period is shown in Fig. 26.

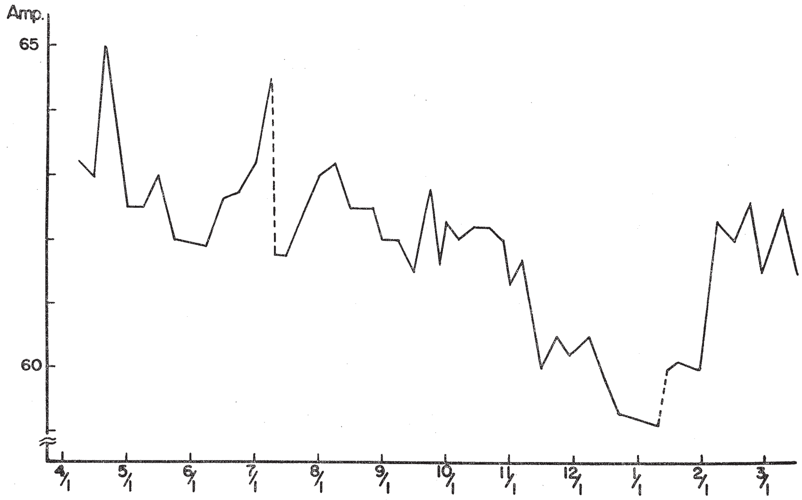


FIG. 26. Variation of electric current of deflection magnet. The ordinate indicates the electric current (Amp) of deflection magnet and the abscissa the date.

4) *Localizing System:* The mechanical alignment of the localizing system was determined to be very stable unless disturbed by external forces. A weekly precautionary check is made to insure that the system has not been disturbed.

5) *Troubles:* The majority of the troubles experienced occurred during first few months of operation. As shown in Table 2, the machine was out of operation for only one day between March 25, 1967 and June 31, 1967 (the initial three months of operation).

CONCLUSIONS

1. A medical 6 MeV linear accelerator was newly designed and developed by the Mitsubishi Heavy Industries, Ltd., Japan. This is the first medical unit made in Japan.

2. Main characteristic point was that electron beam come out from the acceleration tube was deflected two times of 90 degrees, totally 180 degrees deflection. The outline of structure of the unit was described.

3. The size of the X-ray focus is under 2 mm in diameter.

4. The maximum X-ray output is 465 R/min at 1 m under the pulse repetition rate of 500 pps. The X-ray dose-rate is relatively stable as demonstrated by the long-time irradiation test. The initial transitional dose-rate is short in duration (1.1 sec) and negligible in its affect on performance.

5. 6 MeV electron beam also was tested.

6. The mechanical accuracy of the rotation center and the accuracy of the rotation speed of the movable section of the machine were very satisfactory.

TABLE 2. Obstacles of Mitsubishi Linear Accelerator

Date	Symptoms	Cause	Repair	Time required for repair
Apr. 1, 1967	Discharge in magnetron	Life	Exchange of magnetron	24 hours
Apr. 15, 1967	Discharge in magnetron	Trouble of thyratron	Exchange of thyratron	3 hours
Apr. 22, 1967	Unstability of X-ray dose-rate	Trouble of bombarder	Exchange of bombarder filament	20 minutes
May 13, 1967	DeQ inactive	Change of characteristics of thyratron	Exchange of DeQ thyratron	30 minutes
May 17, 1967	〃	〃	〃	〃
May 26, 1967	Action of interlock of low voltage source	Fuse snapping of A.V.R.	Exchange of fuse	20 minutes
June 12, 1967	〃	Trouble of shunt diode	Exchange of diode	1 hour
July 8, 1967	Decrease of X-ray dose-rate	Contact of bombarder with holder	Exchange of bombarder filament	10 hours
July 22, 1967	Discharge in magnetron	Life	Exchange of magnetron	6 hours
Aug. 16, 1967	Decrease of X-ray dose-rate	Trouble of bombarder cathode	Exchange of cathode	20 hours
Sept. 6, 1967	〃	〃	〃	〃
Nov. 16, 1967	Fuse snapping of I.V.R.	Trouble of resistance	Exchange of resistance	10 hours
Jan. 17, 1968	Decrease of X-ray dose-rate	Contact of bombarder cathode with holder	Exchange of cathode	20 hours
Mar. 5, 1968	Scale-out of current meter of bombarder	Trouble of filter condenser	Exchange of condenser	4 hours
Apr. 2, 1968	Trouble of gantry rotation	Trouble of gear	Screwed	5 hours
May 4, 1968	Decrease of X-ray output	Contact of bombarder cathode with holder	Exchange of cathode	20 hours
May 15, 1968	Discharge in magnetron	Life	Exchange of magnetron	10 hours
June 29, 1968	Decrease of cooling water and vacuum reduction		Welding repair	10 hours
July 29, 1968	Non-action of treatment table	Trouble of micro-switch	Repair of micro-switch	24 hours

7. The performances test results met or exceeded the target design requirements.

8. The first year of operation has demonstrated that the unit is highly reliable and can be maintained in service almost continuously.

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