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Publication Date
1966-02-28
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UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

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Jack J. Tait

February 28, 1966
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ABSTRACT

We describe an instrument employing miniature monitor/search ionization chambers to plot dose contours and beam profiles of high-intensity pulsed-particle radiations from the Berkeley 184-in. synchrocyclotron. The instrument utilizes a monitor/search signal-ratio principle to make measurements independent of beam-intensity fluctuations. The search probe is moved in a polar-coordinate system through a water phantom, with the resultant contours or profiles displayed on an X-Y recorder. By simple switching the instrument is converted from an isodose-contour plotter to a profile plotter. A servo system provides semiautomatic control of the plotter in both modes of operation.
INTRODUCTION

In describing completely the radiation dose delivered to any absorbing medium, it is necessary to know both the absolute absorbed dose at some point and the three-dimensional relative dose distribution about that point within the absorber. These factors are particularly important in the irradiation of biological material for both experimental and therapeutic purposes. The therapeutic uses of x and gamma radiation have, over the past few decades, stimulated the development of numerous instruments and techniques for measuring these properties of radiation fields. More recent advances in the uses of atomic energy and in space exploration have stimulated interest in the biological effects of high-energy particulate radiation. In this project we investigated more fully the dose distribution in irradiation of the pituitary gland, utilizing the Bragg peak from a 910-MeV alpha beam at the Berkeley 184-inch synchrocyclotron.

Various methods are available for the measurement of absorbed dose distribution in tissue. A number of detectors suitable for this purpose were described by Birge, Anger, and Tobias. Charged-particle dose distributions are recorded in a number of ways, e.g., by photography, activation dosimetry, point-by-point ionization measurements, or dose-rate methods. All such measurements are normally carried out in a phantom material that has tissue-equivalent properties.

With photographic and activation methods, the distribution from both fixed and moving beams of radiation can be recorded. Since the dose at every point in the detector is measured simultaneously, intensity variations do not affect the resultant recorded distribution. However, with both methods the effects recorded are proportional to the number of particles rather than to the absorbed dose. Accuracy is seldom better than 90 or 95% and there may be pronounced energy dependence in the response of these detectors. Point-by-point ionization-chamber measurements, although accurate and capable of giving moving-field distributions, are time consuming.

For stationary beams only, the dose-rate method is the most direct and rapid way to plot dose contours. This method lends itself to automation in the form of curve-following servo systems. If the monitor detector is used in a ratio circuit with the search probe, the resulting plot of distribution will be independent of radiation intensity. Such a device was first developed by Kemp for x-ray measurements. Numerous similar devices have since been made, and the principle of operation is described in various text books, e.g., Johns.

We describe the development and construction of a plotter for measuring beam profiles and dose contours obtained in a water phantom exposed to alpha and proton beams generated by the 184-in. synchrocyclotron. Although the instrument is limited to plotting distributions from fixed fields in water or air, it is possible to compute from these measurements, by methods commonly used in radiotherapy, e.g., the resultant distributions due to moving fields.
CHOICE OF PLOTTING SYSTEM

Influencing Factors

A number of factors influence the nature of the radiation beam to be investigated:

1. The 910-MeV alpha beam from the 184-in. synchrocyclotron is pulsed at a rate of 64 pps (pulses per second);
2. The pulse length is approximately 60 μsec;
3. A beam current of $10^{-7}$ A gives an average absorbed dose rate of about 1,000 rads/min in water, or approximately 0.26 rad/pulse;
4. The number of particles per pulse, and hence instantaneous dose rate, varies randomly over a range of 20:1 or more;
5. Radiation beams as small as 1 cm in diameter are commonly used;
6. The presence of a strong radio-frequency field around the accelerator requires special precautions to prevent unwanted electrical interference;
7. The existence of a Bragg peak within the measuring area gives rise to servo-phasing problems in some types of plotter.

Detectors

The detector used must be small with respect to the beam being studied; its response must be independent of energy, but must be a linear function of intensity; and its output should be related to biological effect. Either ionization chambers or scintillation counters are commonly used, although some of the newer solid-state detectors may also be suitable. From consideration of the above factors we decided to use carefully designed miniature ionization chambers as detectors. In order to minimize interference, preamplifiers were used to provide a small voltage gain and give low-impedance output to the coaxial cables connecting the measuring cave and the control room.

Plotting System

Most isodose plotters use a system of rectangular coordinates as described originally by Kemp. Mauchel and Johns used a radial (polar coordinate) plotter, and Beasley, Melville, and Knight described an instrument utilizing a scanning movement.

We chose a polar plotting system because it was capable of tracing Bragg-peak contours without phasing difficulties, provided the origin of the polar coordinate system coincided with the maximum dose of the Bragg peak. The scanning system of Beasley et al. would likewise obviate servo-phasing problems but was slower and less accurate than a curve-following system,
since interpolation had to be carried out between recorded points.

MECHANICAL DESIGN

Isodose Plotter

Figure 1 shows the mechanical arrangement used in the instrument. It consisted of a frame capable of rotation, by means of a hand crank and Selsyn drive, around a vertical axis above the water phantom tank. The search probe was mounted on two horizontal lead screws attached to this frame. The lower end of the search-probe ionization chamber dipped into the tank. By means of the lead screws the probe could be moved horizontally along a radius passing through the vertical rotation axis. The probe was driven by a servo motor via Selsyn transmitter and receiver. A precision 10-turn potentiometer, attached to the radial drive, produced a dc voltage $E(r)$ proportional to $r$, the distance from the vertical rotation axis to the center of the ionization chamber. After being operated on by a sine-cosine potentiometer attached to the rotation axis, the voltage $E(r)$ gave rise to two voltages $E(x) = E(r) \cos \theta$, and $E(y) = E(r) \sin \theta$ (where $\theta$ is the angle between the beam axis and the radius of the ionization chamber carriage). Then $E(x)$ and $E(y)$ were applied to the $X$ and $Y$ inputs, respectively, of an $X$-$Y$ recorder that plotted progressive positions of the search probe.

A monitor ionization chamber in the main beam supplied a reference signal with which the search signal was compared. Any difference between these signals caused the servo system to bring the search probe radially into a position at which a null output was obtained. Initially the gain of the search amplifier was adjusted to null output when the probe was centered on the maximum dose point in the water phantom and the dose-level control was set to 100%. When the dose-level control was set to lower values the probe automatically moved radially into a new null position where the percent dose in the beam was the same as that set on the control. When the radial arm rotated through 360°, the complete isodose contour for the percent level could be traced out. A family of curves was plotted by repeating this procedure for all required percent-level settings.

Profile Plotter

By simple switching of the control circuits, the device could be converted to a beam-profile plotter, a very useful facility for studies of beam shape, flatness, and position. Profiles could be drawn parallel to the radiation-beam axis or at any angle relative to it.

After the required profile position and direction were set, the hand-crank control was switched to drive the search probe along its horizontal lead screws. Simultaneously, the servo circuit drove the percent dose-level control via a geared Selsyn receiver attached to its shaft. Another 10-turn potentiometer geared to the level control provided a dc output voltage $E(I)$ that was proportional to the percent-level setting, this in turn being proportional to the beam intensity. If the maximum dose rate in the profile was set to 100%, then dose rates at all other points were expressed in percent of this maximum. The voltage $E(I)$ was connected to the $Y$-input of the $X$-$Y$ plotter, and the voltage $E(r)$ from the radial-arm potentiometer was connected
Fig. 1. Plotter schematic.
to the X-input. The recorder then traced a curve of ionization current (or dose rate) as a function of distance along the line of the profile.

THE IONIZATION CHAMBER PROBE

Probe Design

A schematic and details of the ionization chamber probe and preamplifier are shown in Fig. 2. Design features are similar to those used previously by the author for another isodose plotter. The ionization chamber was permanently connected to the preamplifier with a rigid Lucite stem long enough to keep the amplifier out of the primary radiation field. This method of construction not only eliminated microphonic noise generated by conventional coaxial cables, but also reduced the input capacitance to a low value. All air spaces other than the sensitive chamber volume were filled with non-ionizing insulating material to prevent stray pickup of scattered radiation; white vaseline was very suitable for the purpose, the low melting point facilitating removal of trapped air bubbles and preventing damage to heat-sensitive components such as transistors. It is also easily removed for circuit repairs or modifications. Ceresin wax or other good dielectric material could also be used. The outer surface of the probe, electrically shielded by graphite and silver paint, was finished with waterproof varnish.

The Ionization Chamber

Owing to the small beam sizes to be studied, the dimensions of the detection chamber had to be minimized. For the present device, a chamber size 0.2 cm long by 0.1 cm in diameter (volume approx. $1.7 \times 10^{-3}\text{ cc}$) was considered acceptable. Such small dimensions introduce problems in obtaining sufficient signal strength and low electrical leakage, in addition to the mechanical difficulties of machining and construction. Since the beam to be studied was pulsed and of high intensity, sufficient sensitivity was obtained from this small volume. Leakage was minimized by a guard between the high-voltage and collector electrodes.

Suitable chamber dimensions were calculated from the theory of Boag\textsuperscript{9} to enable high collection efficiency with low applied voltage. Theoretical and actual collection efficiencies are shown in Fig. 3. Differences between the two curves arise first from the fact that high-energy alpha particles rather than x-ray photons are being measured. This fact means that initial recombination, assumed negligible in the theoretical analysis, may in fact be important, especially at low collection voltages. Second, since the instantaneous dose rate per pulse is not constant, a nominal dose rate of 1,000 rad/min (0.26 rad/pulse) may vary instantaneously by a factor of 5 or more above and below this level. This variation reflects in the shape of the saturation curve, which rises less quickly than that for a constant pulse intensity. In spite of this, a collection efficiency better than 95% was attained at the design dose rate for 45 V. At the normal potential of 90 V, the collection efficiency appeared to be better than 99%.

The sensitivity for 100 kV x rays was approximately $5 \times 10^{-15}\text{ A/R/min}$, which is close to the theoretical value.
Fig. 2. Chamber and preamplifier detail.
Fig. 3. Chamber collection efficiency vs supply voltage.
The chamber is of Lucite, with colloidal graphite conductive surfaces. The aluminum collection electrode was 0.3-mm in diameter.

The leakage currents, measured with a dc picoammeter, from the high voltage electrode to guard the ring from the guard ring to collector, were less than $10^{-8}$ A at 100 V. Leakage current between the high-voltage and collector electrodes was less than $10^{-12}$ A.

**Preamplifier**

As shown in Fig. 2 the ionization current from the detector chamber flowed through a 100-MΩ input resistor in the preamplifier, developing a peak voltage of between 0.01 and 0.1 V at the grid of the electrometer tube (CK 5886). The chamber, stem, and tube capacitances, in parallel with the 100-MΩ grid resistor had a time constant of approximately 1 msec. The anode current of the electrometer tube was amplified by a two-stage transistor amplifier, with negative feedback to reduce the overall voltage gain to 8. The low-output impedance of the preamplifier was matched to that of a coaxial cable that carried the signals to the control room some distance from the irradiation cave; this low-impedance line reduced both 60-cycle ac and radio-frequency interference.

The equivalent input rms noise voltage of the preamplifier was 1 mV, which was at least 20 dB below the normal signal level, and even for the 1% isodose curve should not be troublesome because the main amplifier utilized a coherent detection system.

**ELECTRICAL DESIGN**

**Main Amplifier**

Figure 4 shows the principle of amplifier operation and the circuit diagram of the basic amplifier block used. Both monitor and search signals were fed to amplifiers, with gains adjusted to give correct output voltages. The monitor signal triggered a monostable multivibrator with a time constant of 1 msec. This triggering produced 1-msec gating pulses synchronized with the radiation pulses. The outputs of both amplifiers were fed via pulsed gates to a differential amplifier which also had a gated output, integrated to give the dc error voltage which operated the servo system.

A second gain control in the feedback circuit of the search amplifier set the desired percent dose level. This control also had a Selsyn drive which was used when the device operated as a profile plotter. Unlike in most isodose plotting systems, the percent-level control was placed in the feedback circuit of the search amplifier, to provide a constant signal level to the differential amplifier.

The gating system improved the signal/noise ratio, especially at low-intensity input to the search probe. The noise source was predominantly 60-Hz pick up in the long coaxial cables. Since the amplifiers were gated at the same rate as the signal, random noise and 60-Hz noise averaged to zero at the output integrator, whereas the difference signal was either positive or negative, depending on which differential amplifier input was larger.
Fig. 4. Logic diagram of plotter.
Servo and Control Circuits

The output from the main amplifier integrator, fed to a 60-Hz transistor chopper and a servo amplifier, drove the servo motor at a speed and direction dependent on the magnitude and polarity of the input signal. In the isodose mode, the servo motor drove the search probe radially, as shown in Fig. 5(a), via a Selsyn transmitter and receiver. A second Selsyn transmitter-and-receiver system, operated by the hand crank, rotated the search-probe frame around the rotation axis. When the plotter operated in the profile mode, the servo motor drove the percent-dose-level control via the Selsyn system while the hand crank moved the search probe radially across the beam.

Indicator System

The mode of operation of the indicator system of the isodose plotter shown in Figs. 1 and 5(a) has already been briefly described under Mechanical Design. The voltage across the radial potentiometer was adjusted to an $E(r)$ of 1.0 V per in. of probe travel. A second potentiometer in parallel with this set the probe position to the origin of the polar-coordinate system. A push button and relay (not shown in the diagram) returned the probe to the origin. This feature was useful for initial setting up of the instrument, and for subsequent checking during operation. An operational amplifier with a gain of -1 gave both $+E(r)$ and $-E(r)$ inputs required for the sine-cosine potentiometer. Care had to be taken to ensure that the outputs of the operational amplifier were not loaded by the sine-cosine potentiometer, and that the latter was not loaded by the input impedance of the X-Y recorder.

An X-Y recorder (Moseley Model 2D) served as the display system. It did not load the sine-cosine circuits, provided it was not used on ranges more sensitive than 0.5 V per inch.

Figure 5(b) shows the circuit modifications necessary to convert the device into a profile-plotting system. The principle of operation in this mode is also described under Mechanical Design.

CONCLUSION

Although intended originally for pituitary-irradiation studies with alpha beams, the plotter has been shown to have numerous other applications, such as checking for flatness and centering of beam, for rapid plotting of Bragg peaks, and for investigation of the dependence of Bragg-peak shape on the amount and type of absorbing material placed in front of the phantom. Typical curves drawn with the device are shown in Fig. 6.

The instrument functions equally well with proton beams.

By using ion chambers of larger volume, we may extend the range of the instrument to permit the investigation of less intense radiation fields.

Since the preamplifiers are dc coupled, it would be possible to use the device, with modified main amplifiers, to measure steady as well as pulsed radiation beams.
Fig. 5(a). Block diagram of isodose plotter.
(b). Block diagram of profile plotter.
Fig. 6. Representative isodose and profile curves.
ACKNOWLEDGMENTS

The project described in this paper was made possible by an International Atomic Energy Agency Fellowship. The author thanks the Directors and staffs of the Donner Laboratory and of the Lawrence Radiation Laboratory for their encouragement and assistance during the six-month term of this project.

This work was done under the auspices of the U. S. Atomic Energy Commission.

FOOTNOTES AND REFERENCES

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