PHYSICAL PRINCIPLES UNDERLYING THE DEVELOPMENT OF HIGH VOLTAGE ROENTGEN-RAY APPARATUS *

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Until recently, most roentgenotherapy was practiced with voltages up to approximately 100,000 applied to the roentgen-ray tube. The roentgen rays generated at these voltages produced definite biologic reactions at or near the surface of the body. Because of their comparatively low penetrating power, however, these rays were rapidly absorbed by the tissues, and it was difficult to deliver any effective amount to a point much below the surface without injury to the overlying tissue.

Figure 1 gives a visual picture of absorption of roentgen rays as they pass through matter. It shows a cube of lead glass which was placed beneath a half inch opening in a lead diaphragm and exposed for several hours to the rays from a tube operating with four milliamperes at 200,000 volts (peak). This glass becomes brown under the influence of roentgen rays, and the intensity of the coloration indicates the intensity of the roentgen-ray beam at different depths below the surface of the glass. It will be noticed that the color is very dark at the surface and gradually becomes lighter as the depth increases. This illustrates the physical problem involved in deep roentgenotherapy, which, as I have said before, is one of getting sufficient roentgen-ray intensity at a point much beneath the surface of the body.

In the past, the use of multiple ports of entry and of cross-firing was resorted to in an endeavor to increase the intensity beneath the surface. Results obtained by this method are illustrated by Figure 2. In this case, a similar glass cube was exposed from four sides in succession and an area will be seen in the center of the cube where the combined roentgen-ray beams have produced an effect nearly equal to that produced by any one beam at the surface.

During the last few years, the tendency has been toward the use of higher voltages, in an attempt to increase the ratio of depth to surface dose. It is the physical principles underlying this method of attack that I am to review in this paper. Tubes to operate at the higher voltage and apparatus to produce this voltage had to be developed, and the

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experimental work involved in this development was undertaken only after careful physical measurements had shown that a greater intensity at a depth could be produced by the use of higher voltage.

That the results of these measurements may be understood more clearly, let us first consider the beam of roentgen rays coming from any roentgen-ray tube. By means of a Bragg spectrometer and ionization

Fig. 1.—Absorption of roentgen rays in matter shown by color produced in cube of lead glass.

Fig. 2.—Cross-fire technic illustrated by color produced by roentgen rays in lead glass cube.

chamber, we may analyze this beam, and plot the spectrum, just as we would analyze the beam of light from an incandescent lamp. In doing so, we find that it is a composite beam made up of waves of varying lengths. Figure 3 presents a spectrum of the roentgen-ray beam operating at 40,000 volts,¹ and we find that the wave lengths vary from

1. Hull: *Am. J. Roentgenol.*, 1915.

0.3 Å to 0.8 Å,² with a maximum of intensity at about 0.4 Å. We know that the shorter the wave length, the more penetrating power the roentgen-ray wave has, so that we are interested in anything that will give us a shorter wave length and a greater intensity of this shorter wave length.

Figure 4 shows the effect on the wave length and intensity of increasing the potential applied to the roentgen-ray tube. At 40,000 volts, the shortest wave length is about 0.3 Å, and this decreases to about 0.1 Å at 90,000 volts. At the same time, the intensity of the waves of shorter length has tremendously increased. There are still a lot of long wave lengths present, however. The same thing holds true as we go to still higher voltages, as is shown in Figure 5,³ which gives the spectrum at 165,000 volts. Here the shortest wave length is 0.075 Å. The wave length of the gamma rays from Ra-C is approximately 0.004 Å. According to the work of Ellis in England, it would require a voltage of 3,000,000 on the tube to produce roentgen rays of this short

Fig. 3.—Spectrum of roentgen-ray beam from tube operating at 40,000 volts.

wave length. It is evident from these measurements that increasing the potential applied to the tube results in the production of a greater quantity of more penetrating rays.

For the purpose of cutting off the longer or less penetrating rays, it is customary to pass the roentgen-ray beam through some filter, a sheet of aluminum or copper, before it reaches the body. The effect of such a filter is shown in Figure 6,⁴ in which the upper curve shows the spectrum at 70,000 volts without any filter and the lower curve the spectrum with a 3 mm. aluminum filter. It can be seen that the aluminum has reduced the intensity of the soft radiation (long wave

2. The Angström unit, 10^{-8} or $\frac{1}{100,000,000}$ cm. is the standard unit for expressing wave length.

3. Duane: *Am. J. Roentgenol.*, March, 1922, p. 169.

4. Hull: *Am. J. Roentgenol.*, 1915.

lengths) much more than that of the penetrating rays, but there is still a considerable amount of soft radiation left. This could, of course, be considerably reduced by the use of a great thickness of aluminum or a sufficient thickness of some denser material, such as copper, but not without cutting down the intensity of the useful penetrating rays to a small fraction of its original value. But we have already noted the effect of increasing the potential applied to the tube. Therefore, we are able to combine the two, higher voltage and greater filtration, to obtain a sufficient intensity of the more penetrating rays. This is

Fig. 4.—Roentgen-ray spectra from tubes operating at from 40,000 to 90,000 volts.

shown in Figure 7,⁵ where we have plotted the intensities through different thicknesses of copper filters at various voltages of from 175,000 to 298,000. It will be noticed that for any voltage the intensity falls off rapidly with increasing thickness of filter, and that for any one filter thickness, for example 1 mm., the intensity increases rapidly with the voltage. When high intensity of penetrating radiation is desired, there is a strong argument in favor of the use of high voltage with sufficient filtration.

5. Coolidge and Kearsley, Jr.: *Am. J. Roentgenol.*, February, 1922, p. 98.

So far we have been considering the roentgen-ray beam before it reaches the body of the patient. In deep roentgenotherapy, what we are interested in is the nature of the beam after it has passed through a certain amount of tissue on its way to the diseased area. To determine the physical characteristics of the beam within the body, we are accustomed to choose some material, such as water, which has about the same absorbing power as the body, and measure at some desired depth in the water, by means of the ionization chamber, the roentgen-ray intensity

Fig. 5.—Roentgen-ray spectrum from tube operating at 165,000 volts.

with tubes operated at various voltages and with filters of various thicknesses. The results of such measurements are given in Figure 8.⁶ Here we have plotted the percentage intensity beneath 10 cm. of water with the roentgen-ray tube operated at voltages of from 200,000 to 250,000, and with the roentgen rays filtered through 0.5 and 1.0 mm. of copper. With one-half millimeter of copper as a filter, the roentgen-ray intensity beneath 10 cm. of water is 14.75 per cent. of what it is at the surface of the water when 200,000 volts are applied to the tube,

6. Coolidge and Kearsley, Jr.: *Am. J. Roentgenol.*, February, 1922, p. 88.

while it is 17.25 per cent. if 250,000 volts are employed. A similar increase is shown with 1 mm. of copper filter. The curves indicate clearly that, up to 250,000 volts at least, the percentage depth intensity increases with increased voltage and that it is greater the thicker the filter.

A third factor enters into the question of percentage depth dose; namely, that of distance from the focal spot to the surface of the body. In any particular case, the distance from the surface to a point beneath at which the roentgen rays are to be delivered is a constant, and the ratio of this distance to the total distance from the focal spot becomes less as the latter distance is increased. At low voltages, it was impossible to greatly increase the focal spot skin distance because the roentgen-ray intensity decreases inversely in proportion to the square of the distance; that is, the greater the distance, the less the intensity. We have seen, however, that this decrease in intensity may be compensated for by increased potential applied to the tube, and increased filtration of the roentgen-ray beam.

Fig. 6.—Roentgen-ray spectra at 70,000 volts with and without aluminum filter.

As a fourth factor, we have to consider the size of port of entry in regard to its effect on the percentage depth dose. The results of measurements made to determine the effect of varying this factor are given in Figure 9.⁷ These curves show the percentage depth dose beneath 10 cm. of water for rays filtered through 3 mm. of aluminum, 10 mm. of aluminum, and 1 mm. of copper for three ports of entry, 5 by 5 cm., 10 by 10 cm., and 15 by 15 cm. It is evident from these curves that, within these limits, the percentage depth dose increases as the size of port of entry is increased. The explanation of this lies in the fact that roentgen rays in passing through matter generate secondary roentgen rays, and the effect of these secondary roentgen rays is added to that of the original beam. The greater the amount of

7. Krönig and Friedrich: *Physikalische und biologische Grundlagen der Strahlen-therapie*, 1918, p. 122.

matter subjected to the action of the original beam, the greater the amount of secondary rays generated, and, therefore, the greater the percentage depth dose. As has already been pointed out, the shorter the wave length of the roentgen ray, the greater the amount of rays which will pass through a certain amount of tissue. The combination of

Fig. 7.—Absorption curves through copper filters.

higher voltage and larger port of entry is, therefore, effective in increasing the percentage depth dose.

Roentgen-ray tubes and generating apparatus are now available for operation at voltages of 200,000 and some experimental work has been done at voltages of 300,000. The tube developed for this work is of

the hot cathode type with solid tungsten target, similar to that used at lower voltages except that the bulb is slightly larger and the arms somewhat longer, to prevent arcing along the surface of the glass. Experience has shown that these tubes operate most satisfactorily when excited from a high tension transformer with mechanical rectifier, or from a constant potential continuous current machine.

As previously stated, the recent work of Ellis in England shows that we should get, at 400,000 volts, radiation similar to the gamma

Fig. 8.—Percentage depth dose beneath 10 cm. of water.

rays of Ra-B, and at 3,000,000, radiation similar to the gamma rays of Ra-C. Though we may not be able to go to 3,000,000 volts, we may well be able to go high enough to increase materially the amount of roentgen-ray energy which can be transmitted through different mediums.

CONCLUSIONS

1. Increasing the voltage applied to the roentgen-ray tube increases the intensity of the roentgen rays produced. The intensity of the more penetrating rays increases much more rapidly than that of the less penetrating rays.

2. At any definite voltage applied to the roentgen-ray tube, increasing the thickness of filter decreases the roentgen-ray intensity but increases the proportion of the more penetrating rays in the roentgen-ray beam beneath the filter.

3. With a definite thickness of any filter, increasing the voltage increases the ratio of depth to surface dose.

4. With a definite voltage and filter, increasing the target skin distance increases the ratio of depth to surface dose.

5. Increasing the size of the port of entry increases the ratio of depth to surface dose.

6. Roentgen-ray tubes and generating apparatus are available for operation at 200,000 volts.

Fig. 9.—Effect of size of port of entry on percentage depth dose.

ABSTRACT OF DISCUSSION

DR. WILLIAM ALLEN PUSEY, Chicago: We are under obligations to the physicists for introducing waves of higher voltage and shorter wave length but deeper penetration. Anyone who said such things are not useful would be stupid, but I would call attention to the fact that for the present these are technical, physical problems rather than problems in therapeutics. There is undoubtedly a propaganda for the use of roentgen-ray apparatus to produce enormous voltage. Many factors are involved in that problem about which we are uncertain. It is undoubtedly true that when we get more familiar with the use of roentgen-rays produced by such high voltage we will be able to attack deep lesions with more intelligence than we can now. I would, however, point out that in undertaking to treat these lesions with this new method we are not working with more intelligence than we have had. I know in the old days, when we treated with the old gas tubes, we were able to produce appreciable effects in deep lesions. I am sure no one who has seen a myoma of the uterus treated by this method will doubt that we could produce deep effects then. With the new apparatus, we have to know how much effect we are producing and how much effect we are getting. There is considerable difference in the opinion regarding this—one that the effect is produced by the direct

voltage and the other that it is produced by the square of the voltage. We should keep an open mind and I think we are not yet in a position to be convinced that these enormous voltages are what we need. Recently I had the opportunity to see the work of Barlow with enormous doses of radium in animals. The deep effects produced in animals were exactly analogous with the effect produced on the skin by roentgen rays. They were so strikingly similar that you could almost use the one set of photomicrographs to illustrate the work. The chief thing that came to me in seeing this work of Barlow was the seriousness of an attempt to bombard a man's internals with this enormous penetration. I would not like to be regarded as undertaking to minimize the usefulness of the experiments presented today by Mr. Moore, but I would exercise the caution of a, perhaps, congenitally conservative man by saying that these questions before us are largely academic.

DR. HAROLD N. COLE, Cleveland: I was much impressed with the fact that with a certain voltage, after you have used a certain amount of filter, no matter how much filter you use you get the same straight line of intensity. I should like to know about the amount of filter indicated with a machine with 60,000, one with 80,000 and one with 120,000 volts, respectively. This is a very important point and if you reach a certain amount of filter and no more will make any difference in the line, that is something we should know about.

DR. F. J. EICHENLAUB, Washington, D. C.: As dermatologists, I am sure that we have learned a great deal from this paper. I think the facts brought out by Mr. Moore demonstrate that the dermatologist will never need the 200,000 volt machine. Furthermore, the statement that filtration decreases the intensity is very interesting, because it strengthens the plea of Dr. MacKee that the rays we want in dermatology are the unfiltered rays. In dealing with basal cell cancer, acne, and other diseases of the skin for which we use the roentgen rays, we want the unfiltered rays which give the greatest intensity in the superficial tissues.

DR. WILLIAM H. GUY, Pittsburgh: As dermatologists, we are, of course, vitally interested in the physical properties of roentgen rays, and are in sympathy with all attempts to improve apparatus and technical details. However, the bulk of our pathology is very superficial and we use by preference unfiltered rays with moderate powers of penetration, using the minimum amount that will prove effective. Heavy dosage of highly penetrating rays may produce deep seated vascular changes that are not only unnecessary but are also likely to be productive of late undesirable results. By increasing the distance between the anode and the skin, one may reduce the enormous disproportion between surface and depth dosage due to divergence of rays. When additional penetration is desired, filters are indicated. I am rather skeptical as to the highly touted value of these very high voltage machines; certainly in dermatologic practice they are not needed.

DR. C. N. MOORE, Schenectady, N. Y.: Any discussion of the particular results obtained by the use of low or high voltage is, of course, entirely out of my province. The answer to the question as to what type of rays produce the best results should be left to the physicians who apply the rays. One point I would like to correct in Dr. Pusey's discussion, and that is the impression that you may have roentgen rays so penetrating that they are not absorbed at all in going through matter. It is a physical fact that roentgen rays of any kind are absorbed to a certain extent. A definite thickness of matter will absorb a certain percentage of the rays and the next equal thickness will absorb

the same percentage of those rays which were not absorbed in the first layer. In regard to Dr. Cole's question as to the proper thickness of filter to use at the various voltages employed in roentgen-ray work, it would depend on what intensity was desired beneath the filter. As you remember, the curves showing the relation between intensity and filter thickness for any definite voltage indicated that the intensity always decreased as the filter thickness was increased. The fact that the curves became straight lines beyond a certain filter thickness simply showed that further filtration did not change the quality of the roentgen-ray beam.