A BIOLOGICAL CALIBRATION OF AN X-RAY DOSIMETER

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The purpose of the experiments described in this paper is to test, by means of a quantitative biological method, the accuracy of the Victoreen dosimeter in measuring X-ray dosage in Roentgen units. That dosage should be defined more accurately than by a statement of the voltage, amperage, filtration, and time, has long been realized, but until recently a more accurate definition has not been possible because there was no generally accepted method of measurement and no standard X-ray unit. Fortunately these matters have now been agreed upon, and measurements of considerable accuracy are being made. These show that doses which, according to the old standards, are similar, may actually be very different, even though the physical conditions under which they are produced appear to be alike.

There are many reasons why the output of different machines varies even when the voltage, milliamperage, and filtration appear to be the same in both. One is that no two tubes are precisely alike. If the wall of one is slightly thinner than that of another, the output, especially of soft rays, will be very much greater. According to Coolidge and Kearsley (1) the extreme difference between tubes of the same manufacture may be 87.5 per cent, though usually it is much smaller. If the beams are filtered through copper the difference is less than 10 per cent. These tests were made on new tubes. Old tubes with targets roughened by long usage may lose 40 per cent of their efficiency.

Another source of variation is the wave form. When the machine is equipped with mechanical rectifier, the output is pulsating, the voltage half of the time falling practically to zero. During these intervals no X-rays are produced. If rectification is made by means of kenotrons the output is continuous but fluctuating. Suitable condensers will smooth out these small variations in potential so that the production of X-rays can be made practically uniform. Obviously, when machines of the two types are operated at the same voltage, the actual output of the second type will be far greater than that of the first.

The biological effect of beams of these types has been investigated by Wood (2). Mouse tumors, irradiated at 120 KV. and 5 Ma. through 3 mm. of aluminum, were inoculated into healthy animals. The length of exposure needed to kill the tumor cells so that no takes resulted was 65 minutes for the interrupted current, and 35 minutes for the continuous, the difference in effect being nearly 100 per cent. The continuous current in these experiments was completely rectified by means of four kenotrons and large condensers. In the commercial X-ray machines equipped with valve tubes the potential fluctuates somewhat, for rectification is not complete. For this reason the difference between their output and that of a mechanically rectified machine will be less than that found by Wood.

The wave form may be varied in either type of machine by setting the contacts on the control board in different ways. The intensity of the beam will vary also. I have tested this point on a Wappler Diex machine, using a Victoreen dosimeter to measure the intensity. The voltage, milliamperage, and filtration were constant in each experiment. The results are shown in Table 1.

TABLE 1

	Settings			r/min.	500 r
	Large Trans.	Small Trans.	Rheostat		
100 KV., 6 Ma., 1 mm. Al	2	2	18	45.29	11.0 min.
	3	3	9	25.18	19.8 min.
	3	8	6	21.64	23.1 min.
130 KV., 4½ Ma., 1 mm. Al.	3	1	18	29.73	16.8 min.
	3	3	15	26.97	18.5 min.
	3	9	9	21.02	23.8 min.

When the resistance through the rheostat is cut down as much as possible, the intensity is at a maximum, and it falls as the resistance is increased. This effect is more noticeable at low voltages than at high. At 100 KV. the extreme difference is more than 50 per cent. Thus a dose of 500 *r*-units may be given in 11 minutes or in 23 minutes, depending on the setting of the control board. At 130 KV. the difference is less but still large enough to be important.

Feldweg (3) has called attention to the fact that the condition of the kenotrons, whether new or old, has an important effect on the potential. In one of his experiments the voltage indicated on the meter was 210 KV. 1 mm. of copper was used as a filter. The half value in copper of the filtered beam was 1.3 mm. when the valves were new, and 1.1 mm. when they were old. The voltages corresponding to these values are 180 and 160 KV. respectively. Thus there was a loss in potential amounting to 11 per cent. These changes in the kenotrons are gradual, and the decrease in voltage which they produce is not shown by the meter.

Perhaps the most important source of variability is found in the voltmeter and milliammeter which, according to Fialla (4), are "utterly insufficient" for accurate measurement. It is evident then that a dose cannot be adequately described by stating the voltage and milliamperage as they appear on the meters, for these instruments do not correctly show the quality and the quantity of the radiation.

Dosage is more adequately measured in terms of the amount of ionization which X-rays produce in air. Air is used as a standard because the absorption of the rays by it and by tissues is roughly parallel. The large ionization chambers used in these measurements are, when properly constructed, very accurate, being independent of the wave length. However, since they cannot be used conveniently in measuring depth doses, or skin doses on the patient, small ionization chambers have been devised. These are constructed on the principle that if the walls are made of a substance which has the same effective atomic number as air, and hence the same beta ray emission, they should measure ionization as well as the large air chambers (5). The material for the walls may be graphite combined with some other substance, such as magnesium, silicon, or cellophane. The various types of chambers, the details of their construction, and their accuracy, as compared with the large air chamber, are discussed by Braun and Küstner (6), who find that a properly designed instrument may be practically independent of wave length and accurate within $\pm$ 6.3 per cent. Küstner (7) in a review of the whole subject concludes that thimble ionization chambers, even though they are not perfect, are of value in therapy where great precision is not essential.

The older chambers, constructed of aluminum or horn, whose atomic weights are greater than that of air, were not independent of wave length because of the large amount of absorption in the walls, especially when the radiations were soft. With such instruments it was impossible to obtain doses of equal intensity with different voltages. For this reason, some of the conclusions regarding the relative biological effects of long and short waves have had to be revised.

EXPERIMENTAL

I have tested the Victoreen dosimeter (1928 model) by the biological method. This consists in radiating the eggs of *Drosophila* and determining the proportion of eggs that hatch after radiation. Experience has shown that when they are subjected to a definite number of *r*-units a definite proportion hatch; the remainder are killed. For example, 75 per cent hatch after a dose of 125 units, and 50 per cent after one of 180 units. Variations in the quality of the beam are without effect; the intensity is the important factor. The eggs are in themselves good ionization chambers. The curve showing the per cent of eggs hatching after various doses, measured in *r*-units by an open ionization chamber, is shown in Fig. 1.

This curve is of value in estimating dosage. If a beam of unknown intensity kills half of the eggs in 10 minutes, the dose must have been approximately 180 *r*-units, delivered at the rate of 18 *r*/min. One such test is not enough, for statistical analysis shows that the error of a single observation may be as great as 8 per cent, although in the majority of cases it is less than 3 per

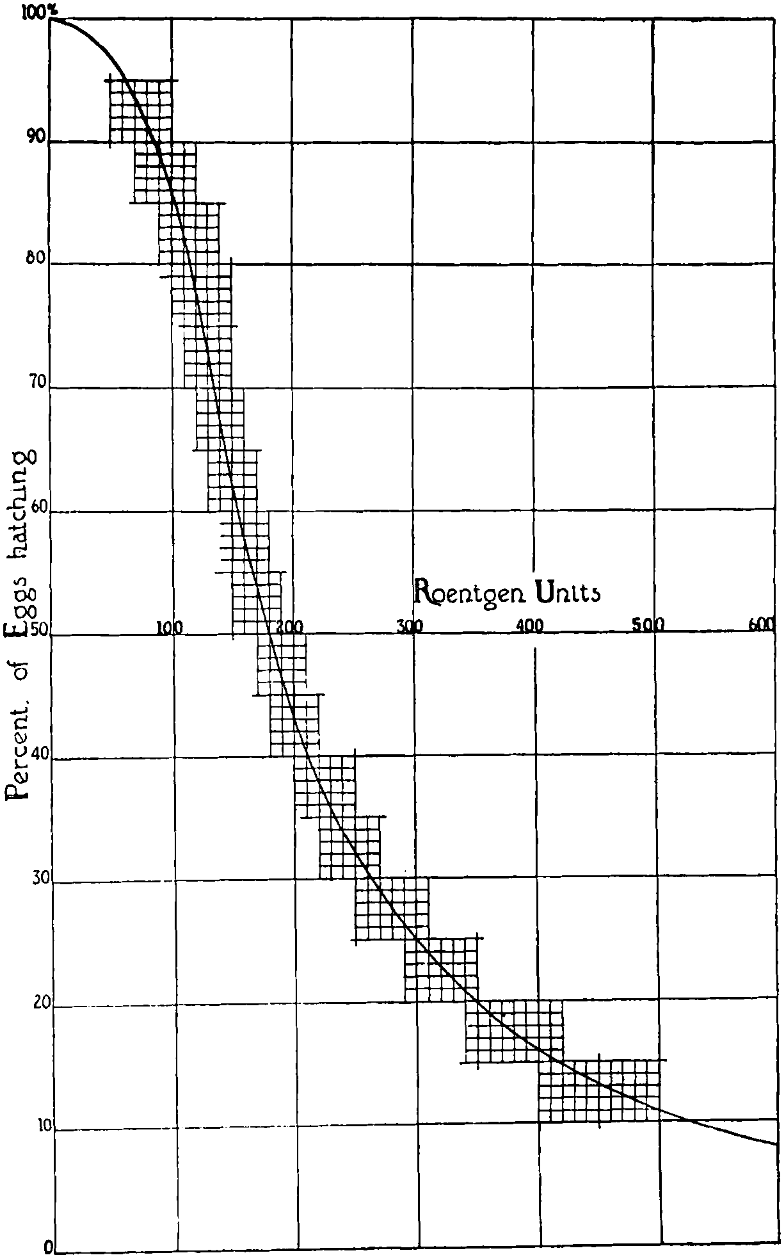
100%
90
80
70
60
50
40
30
20
10
0
Percent. of Eggs hatching
Roentgen Units
100
200
300
400
500
600

FIG. 1.

cent. When three or more tests are made under similar conditions, the weighted average will be within 2 per cent of the correct value.

The curve cannot be used safely for estimating very small or very large doses, that is, those after which more than 95 per cent or less than 25 per cent of the eggs hatch, for in these regions it approaches the horizontal where small variations in the biological results make very large differences in the indicated number of *r*-units delivered. If the average of three tests shows that 10 per cent of the eggs hatch, the probability is that 490 *r*-units have been delivered. But the true value may lie between 8 and 12 per cent, corresponding to doses of 550 and 440 *r*-units respectively. This difference is so great that a calculation of the dose is of little value. But in the steep part of the curve this amount of variation in the biological result is comparatively small. For example, if 50 per cent of the eggs hatch, the true value may lie between 48 and 52 per cent, corresponding to doses of 185 and 175 *r*-units respectively.

In these tests on the efficienty of the Victoreen dosimeter, the voltages used were 60, 100, 150, and 200 KV. The first three were obtained on a Wappler Diex machine having thermionic rectification; the test with 200 KV. was made on a mechanically rectified machine. I made no attempt to arrange the doses so that an equal number of *r*-units, as indicated by the dosimeter, should be delivered in equal times under each voltage, for this is not essential. However, the intensity should be more than 5 *r*/min., for when it it less the dose is subminimal and only the most sensitive eggs will be killed, the rest remaining alive even after long exposures.

This is an important matter which is frequently lost sight of in experiments of this kind. It is often assumed that the only change occurring in living cells or organisms during exposure to a harmful agent, such as X-radiation, is due to that agent, and that other than this, the biological material is the same at the end of the exposure as it was at the beginning. Such an assumption neglects the fundamental biological principle that all living matter is continually adjusting itself to changes in its environment. When these changes are harmful the organism responds by attempting to repair the injury. If the rate of repair is equal to the rate of injury the organism will continue to live, even though the injurious agent acts for a long time. This is seen in the behavior of *Drosophila* eggs exposed to X-rays having an intensity of 4.5 *r*/min. After 105 minutes of continuous radiation 91 per cent of the eggs hatched. Since about 450 *r*-units had been delivered we should expect, from an inspection of the curve, that only 12 per cent should remain alive. In tests with very weak doses the Roscoe-Bunsen law obviously does not apply. The intensities employed in the experiments reported in this paper ranged from 10 to 16 *r*/min. and the longest exposure was 20 minutes.

In each test, the Victoreen ionization chamber was firmly supported on a gauze strip. There was no appreciable back scatter from this. Care was taken to protect all parts of the instrument from stray radiation, a precaution especially necessary when the highest voltages are used. The eggs were placed at the level of the middle of the ionization chamber and as close to it as possible. When the dosimeter showed that the desired number of *r*-units had been delivered, the eggs were removed and kept in a moist chamber at room temperature for two days, when they were counted and the proportion of hatching eggs determined. The number of *r*-units required to kill this percentage of eggs is found on the curve and compared with the number indicated by the dosimeter. Since the biological method is accurate within narrow limits, these numbers may be taken as a standard. If the two are approximately the same, the dosimeter measures correctly; if they are different, the amount of error of the instrument can be calculated.

The results of the four series of experiments are summarized in Table 2, which shows the voltage, milliamperage, and filtration used in each test. Next to these data appear the number of *r*-units delivered, as indicated by the dosimeter. The following four columns give the number of eggs alive and dead after exposure, the actual percentage of eggs hatching, and the corrected percentage. The latter is obtained by dividing the former by

97, this being the proportion of eggs that hatches in the unradiated controls. The succeeding column gives the number of *r*-units which the mortality curve indicates as the real dosage. The figures in the last column indicate the accuracy of the dosimeter readings reckoned as percentages of the biological readings.

TABLE 2

	r-Units Dosimeter	No. of Eggs		Per Cent Hatching		*r*-Units from Curve	Per Cent Correct
		Alive	Dead	Actual	Corr.		
60 KV., 5 Ma., 1 mm. Al.	110	246	90	73.2	75.5	125	87.3
	122	207	116	64.1	66.1	143	
	182	143	214	40.1	41.3	206	
	414					474	
100 KV., 5 ma., 1 mm. Al.	121	459	173	72.6	74.8	126	96.9
	168	234	242	49.2	50.7	178	
	177	529	602	46.8	48.2	185	
	265	236	630	27.3	28.1	265	
	731					754	
150 KV., 5 ma., ¼ Cu and 1.0 Al.	127	736	310	70.5	72.7	130	100.7
	187	513	580	46.9	48.4	184	
	282	102	304	25.1	25.9	278	
	596					592	
200 KV., 8 ma., ½ Cu and 1.0 Al.	70	350	34	91.2	94.0	67	98.3
	80	178	24	88.1	90.8	83	
	125	188	52	70.8	73.0	130	
	180	276	307	47.3	48.8	183	
	455					463	

The data show that the ionization chamber is not entirely independent of changes in wave length; it does not correctly measure the intensity of soft radiation produced at 60 KV. The error is calculated by dividing the sum of all the dosimeter readings in this test by the sum of the *r*-units which the biological test indicates were actually delivered to the eggs. The quotient is 87.3 per cent; that is, the dosimeter measures about 13 per cent too low at this voltage. A few tests made at 90 KV.

(not given in the table) show that the error at this voltage is about 8 per cent.

Between 100 and 200 KV. this ionization chamber is practically independent of wave length. The error at 100 KV. is 3.1 per cent. This is about the size of the standard deviation, but probably it is significant since the differences from the doses indicated by the curve are, in every case but one, in the same direction. At 150 KV. the two sets of readings are the same; the instrument therefore measures accurately here. At 200 KV. the figures are also in good accord. Within the usual range of X-ray therapy, this dosimeter measures dosage with reasonable accuracy.

The biological method of estimating dosage, while accurate, is time-consuming, for sometimes the flies do not furnish enough eggs to work with, or the eggs do not show the high degree of fertility which is a prerequisite for a good experiment. The dosimeter indicates the dosage in a few minutes. The eggs have not, however, lost their usefulness in measuring dosage, for they are constant in their response year after year, and different strains are equally susceptible. On the other hand, the dosimeter is a delicate instrument which must be frequently calibrated. And unless there is some check on its performance one cannot be sure whether it is measuring correctly or not. That fly eggs provide a good standard for comparison is shown in the results of tests in which the dosimeter registered a dose of 20.7 *r*/min. while the biological test indicated a dose of 14.8 *r*/min. The difference was probably due to a lack of adequate protection against direct and scattered rays which penetrated the insulation of the dosimeter. Although the X-ray tube was surrounded with 8 mm. of lead, the electroscope in the dosimeter continued to discharge when the ionization chamber was far removed from the path of the rays. The rate of discharge, tested on several occasions, was 6 *r*/min. That is, the measured intensity exceeded the true value by this amount. The actual intensity of the beam, measured by the dosimeter, was therefore 14.7 *r*/min., a value which is practically the same as that furnished by the biological test.

SUMMARY

The Victoreen dosimeter (1928 model) has been tested by means of the biological method, the value and limitations of which are discussed.

The dosimeter records dosages correctly when the voltages range from 100 to 200 KV. Below 100 KV. it fails to register the full intensity.

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