A DISCUSSION OF THE METHODS USED FOR MEASURING ROENTGEN-RAY APPLIED INTENSITY

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Ever since roentgen rays and radium were discovered, there has been dissatisfaction with the methods which have been proposed or employed for measuring their intensity. Since the inaccuracies of each of these methods have been discussed in the literature, every radiologist should know that the chemical and biological as well as the mechanical methods cannot be depended upon in measuring the intensity or quality of radiation, or what has been commonly called "dosage."

When the roentgen rays became generally employed in the treatment of disease, it was found that there is a limit to the amount of radiation which can be applied to the human skin without causing undesirable sequelae. This limitation, manifested by various degrees of redness or tanning, was called the "erythema reaction." It is unfortunate that this reaction of the skin has been retained as a biological standard of dosage in therapy, and that we still try to employ it to determine the effects of radiation, and visualize it to limit treatments. Erythema means only redness. The term in no way explains the effects of radiation on pathological lesions. The degree of redness depends upon many factors such as the acuity of color vision of the observer, the interval of time elapsing between the administration and observation, the complexion and age of the patient, the ability of the vascular system to react, the volume and characteristic structure of the subcutaneous tissues which are irradiated, to say nothing of physical factors, such as the quality of the rays.

A unit of erythema has been defined as "that dose which in 80 per cent of cases treated produces a faint reddening or bronzing of the skin in from ten to twenty days, and in the other 20 per cent produces no visible effect." Another definition is: "An erythema dose, or skin tolerance dose, is the amount of radiation that will produce defluvium of the scalp in three weeks, or a pronounced reddening of the skin in a young blonde, on some sensation area in about five to seven days after radiation." These definitions indicate that the erythema dose, or the erythema reaction, is inconstant and indefinite. According to the first definition, in at least 20 per cent

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of cases the reaction does not occur. It would seem, therefore, that such a unit would be unsatisfactory as a standard or as a measure for comparison of physical factors because if the erythema reaction were considered to be constant, then in at least one-fifth of the instances, one could not be sure that physical factors had been correctly controlled. On the other hand, if we assume that the physical factors have been accurately controlled and there is at least 20 per cent variation in skin manifestations, it is apparent that in a large proportion of instances the erythema reaction must fail as a standard measure of physical factors.

The second definition in its first phase bases the erythema reaction upon the epilating effect, and in its second phase upon about one-half of the latent period of the first definition and even specifies a blonde skin and a sensation area. Neither of these definitions takes into consideration the influence of different qualities of radiation. For example, when using hard radiation, epilation occurs with about 50 per cent of the intensity which will cause an erythema, while with softer radiation a much larger dose is required. With the softest radiation (Grenz rays) there is no epilation whatever. Moreover the fact that the definition requires a sensation area indicates that even in the same individual the skin reacts differently in different regions of the body.

A unit erythema dose cannot be divided on the basis of the degree of skin reaction because less than that amount of radiation intensity which should cause a certain degree of redness will produce no visible erythema. Moreover, although in the past we have assumed that a certain proportion of the applied intensity or of the period of application of radiation will produce an exactly proportionate and similar tissue response, we have sufficient evidence to prove that from a biological viewpoint this theory is entirely erroneous. There is not, and never can be, a standard procedure for the application of therapeutic radiation, either as to intervals between treatments or as to the intensity or quality employed. In the case of roentgen rays and radium, therefore, we find that there are individual indications and personal preferences for intensive, divided or saturation technique, which have been shown to produce very different biological effects in pathological and normal tissues. It is obvious, then, that we cannot measure or analyze the results of these different techniques by erythema reaction when the skin unit is established on the basis of an erythema which is produced at a single application. These methods of administering treatment may be limited by the reaction produced in the normal skin; how ever, their effectiveness does not depend upon the skin reaction but upon the energy which reaches a certain volume of pathological tissue and is absorbed in a specified period of time. Therefore, the "erythema dose" cannot be used as a standard for indicating the results of tissue response of different methods of treatment.

No study of skin reaction has disclosed the reason for the effect of radiation on diseased tissues *in vivo*, although we have assumed that with equal intensities the vascular reaction in the deeper tissues is similar to that which takes place on the surface. It cannot be stated positively how these vascular changes affect a neoplastic process, and we have evidence that the somewhat temporary interference with the vascular supply which may be produced by radiation is of secondary importance as compared with the direct destructive effect upon neoplastic cells. Normal skin and malignant tissues are usually of dissimilar histological structure and biogenesis, and *in situ* probably have little in common either as to the degree or kind of reaction to radiation. This is illustrated by the well-known fact that most malignant processes which develop in the skin require vastly more radiation to destroy them than does the normal skin, and that for each malignant tissue — and probably for normal structures as well — there is an optimum destructive intensity. Also the intensity which reaches subcutaneous areas is much less than that which produces the skin manifestation, and is of an entirely different quality, so that the radiation which affects the deep tissues no doubt causes very different effects from those produced by direct radiation, which is measurable. Therefore, the skin erythema dose cannot be applied as a measure of the reaction of pathological tissues to radiation.

Perhaps the most accurate and valuable study of the underlying causes of radiation erythema was originally developed by David and Gabriel who examined the skin capillary reaction by means of special microscopes. This is, of course, a study of the effect of the application and gives no information as to the degree of intensity which is applied, or the degree of reaction which may be anticipated, nor do the originators of this investigation make any such claim for it.

In addition to the skin reaction, several other biological standards has been advocated. For example, it has been suggested that germinating beans (Jungling), *Ascaris* eggs (Holthusen), and the ova of *Drosophila melanogaster* (fruit fly) (Mavor, Packard and Wood), be employed to standardize radiation effects. We have had some experience with each of these methods and the last seems to be the most practical one for laboratory investigation. Later, we hope to report some of the results which we have obtained with it. However, at this time we may say that the procedure is not so simple as one might be led to believe. It is not simply a matter of enticing some fruit flies into a bottle, housing them, and by feeding them upon a proper diet, encouraging them to lay an unlimited supply of eggs to be used *ad libitum* in the laboratory or upon patients. The rearing of these insects is fraught with many complexities with which clinicians have neither the facilities nor the time to deal. These flies, like human beings, are temperamental, and have their gastronomic fantasies and sexual idiosyncrasies; they are subject to diseases and hazards of existence which influence their reproductive activity, the mortality rate and the maturation of the ova, so that sometimes it is difficult to draw accurate conclusions as to the effects of radiation upon them.

It would seem, therefore, that biological methods as standards for estimating the degree of reaction to radiation are unsatisfactory because the reaction of cells or any organism is entirely too variable to be an index of physical mensuration. To attempt to adopt biological methods for the measurement of such physical agents as roentgen or radium rays would seem to be as consistent as to try to measure the heat of a flame by the degree of browning of a steak, or to estimate a mile by the respiratory rate of a runner.

I do not wish to imply that we should entirely disregard the skin of the patient, but after all, the only skin manifestation in which the radiologist is really interested, as far as the effects of his treatments are concerned, is the "tolerance limit." This has been variously named "skin tolerance dose," "maximum erythema dose," etc. Since the term "dose" in a physical sense, is ambiguous, a better term might be "applied intensity," and we might substitute the term "radiation tolerance limit" for the many expressions used in the attempt to describe any limit of tissue tolerance. We must remember, however, that "tolerance limit" is also a rather indefinite term on account of differences in biological reactions which are dependent upon the physical factors which cause them, and upon the metabolic status of the patient's skin at the time of treatment, which in turn depends not only upon the condition of the vascular system as a consequence of certain diseases or of age, but also upon the area of the body which is being treated, and the impressions of the observer. There never can be an absolute "standard minimum," "standard threshold," "standard maximum" or "standard tolerance limit" of erythema skin reaction. As a matter of fact, all of the terms which apply to the reaction of the skin are expressions for the safe limits which are imposed upon the radiologists by the rest of the medical profession, the law, and insurance companies, without regard to the nature of the condition which is being treated, or the judgment and skill of the therapist.

Of course, there is a limit beyond which the radiologist dare not proceed, but this tolerance limit should not be expressed in terms of redness or bronzing but in physical units of measure, a certain number of which, administered under specified conditions, within a stated time, and with a definite quality of radiation, will be the average limit of skin tolerance. We must remember also that the tolerance limit or any other term used to indicate the safe skin reaction is only an average and is not at all indicative of the intensity which is applied to an area under treatment, and is therefore not a measure of the reaction which will take place in a diseased tissue, although this may be calculated on the basis of the percentage absorbed.

The dissatisfaction with the old methods of describing and measuring radiation intensities led to the really epoch-making suggestion of Szilard and Villard, which was later developed by Duane and Friedrich, that a standard physical unit of radiation intensity might be established on the basis of another property of short wave lengths known as the ionization of gases and that the resultant electrical effect of this ionization could be measured as a current in terms of the universally accepted electrostatic unit. The apparatus which was used to measure the ionizing effect was what is now called the "air ionization chamber," and the electrical current produced was measured by means of the galvanometric or the electrometric method.

Extensive investigations have amply confirmed the original work of these investigators and the practicability of the method, many details of which have been perfected. During these investigations numerous and varying types and arrangements of the original air ionization chambers have been employed in widely separated laboratories, in each of which experiments showed that certain mechanical details of design were preferable or essential in order to obtain the most accurate and constant results. These different mechanical factors, each of which influences the measurements of radiation, have now come to be very well known by experienced investigators.

After several years a comparison was made of the results which had been obtained in a number of laboratories where somewhat different mechanical systems had been employed. It is most gratifying, although not particularly remarkable, that these results agreed within very narrow limits of experimental error.

As the result of this agreement, the ionization method of measuring roentgen-ray intensities was accepted at the Second International Congress of Radiology in 1928, and on this basis a standard physical unit was defined. It is worthy of remark that the committee of the Congress was wise enough not to establish or suggest a specific design for a standard air ionization chamber. This decision was owing, no doubt, to the fact that those members who had actually carried on researches with air ionization chambers were already familiar with the different types, their modifications, and numerous details of construction, and recognized the restrictions and limitations which are necessary in order to obtain accurate measurements, and they appreciated that there can be little deviation from certain fixed principles. This applies particularly to such minutiae as diaphragm placement, the size and shape of the diaphragms and their relation to each other, or to the electrodes, and the focus of the tube, and also to the air volume and electric saturation and distribution of the electric fields of the chamber.

Undoubtedly, the next International Congress will find it necessary to make a definite regulation for a preferred design of a standard air ionization chamber in order to remove the doubts in the minds of some physicists and many clinicians who are uncertain as to the accuracy of the "r" as a unit, because of the apparent dissatisfaction of a few who seem to be unwilling to accept the conclusions which have been reached by others. Some dissenters are quibbling about details which have been long understood by those who have actually carried on investigations, and who have had sufficient experience to know which methods are accurate and practical. These dissenters, however, cannot destroy the general principles which underlie this internationally accepted method for measuring short wave length radiation intensity, nor do they present a better method, and their destructive criticisms do not detract from the excellent results which have been achieved. It is enough to know that an international body of eminent physicists and clinicians have come to a complete agreement after a prolonged, painstaking study of the entire problem.

The greatest possible accuracy in determining both quantity and quality is essential in the research or standardization laboratory. It is desirable also in clinical application, but here we are permitted much more latitude.

The factors which influence the measurement of intensity by means of air chambers and the influence of these factors on the accuracy of determinations are so well known by experienced investigators that further discussion is unnecessary. In practical experience, many of these minor factors will not affect, beyond safe limits, the amount of radiation which is applied to a patient, although they do influence the standard unit to a slight degree. Therefore, the clinician is not interested in arguments about minor features which do not influence the method as a whole, or discussions of nonessentials which only tend to confuse and discourage him. It would seem that it is necessary only that physicists agree upon a practical working scheme and design of a standard chamber, whether or not it is theoretically ideal. During this period of transition it is desirable and even necessary for clinicians to have confidence in the theory and practicability of the "r" as a standard of physical measure, and they may be assured that there is no such thing as a new type of air ionization chamber which will in any way influence the "r" as a unit. Of course, from time to time, someone will advocate archaic or unusual arrangements which may change the appearance of the air chamber, but will not affect its performance in any way what has not been demonstrated previously or discarded.

The question of the site at which applied intensity is to be measured in therapy would seem to be a matter of personal preference. However, it should be obvious that it is the amount of radiation which is applied to the patient under certain conditions that is important and must be measured, ~~and not the intensity~~ at any other point. In our clinic we have always advocated the direct method of measuring applied intensity because we prefer to measure at the site of application on the patient. After a number of years of experience and a trial of both the indirect and the direct method, we have found the direct method with a small ionization chamber to be accurate and very simple, not only because calculations, which yield a high percentage of error are eliminated, but because the total applied intensity which the patient actually receives is included in the measurement irrespective of (1) the potential, (2) the filter, (3) the amperage, (4) the distance, (5) the size and shape of the field, (6) the volume of tissue, and all of the other indeterminable factors which influence direct and scattered radiation. We have been especially satisfied with this method since the development of the small air wall type of ionization chamber because we can duplicate or measure accurately the applied intensity of any quality of radiation which we use ordinarily in therapy.

However, in another laboratory, it may be thought preferable to measure the intensity in air at an arbitrary distance from the focus and attempt to estimate the amount of backscattering on the basis of that which takes place in a phantom, and then attempt to interpret these findings in the terms of applied intensity on the patient. It is apparent that all of the six factors which I have enumerated must be taken into consideration in calculating the amount of intensity which is applied at a treatment.

It has been stated that there would be less error if the applied intensity were measured, under fixed conditions, in a phantom, and the standard results applied to patients, because the backscattering from the phantom is always the same. Unfortunately, the backscattering from patients is never the same, and is always different from that from a phantom. These are exactly the differences in which we are interested and which must be taken into consideration, which cannot be done accurately by any indirect method. We are concerned with the intensity which affects the patient, and not with the influence of the radiation on a box of wax.

These observations apply also to the method of calculating the applied intensity by means of standard absorption charts and of measuring or controlling the intensity output with large ionization chambers. The large chamber is usually placed near the tube or under the filter so that only the focal radiation is measured. This method is very valuable as a method of controlling the intensity output, but does not measure the total applied intensity since scattered radiation must be calculated. Those who use these large chambers and criticize the small chamber method lose sight of the fact that the small chamber may also be used in the same locations in which the large chamber may be used and also has many other advantages, and can be used for any quality of radiation.

Those who employ these indirect methods and standard charts with percentage allowances for backscattering cannot take into consideration the fact that the backscattering varies considerably in different regions of the body. For example, between the chest and lumbar fields, there is a difference in backscattering of approximately 15 per cent. Also, the amount of scattering depends upon the wave length employed, increasing as the wave length shortens. The shape of a field is as important as its size since the scattering from a square field 10 by 10 cm. is not the same as that from a field 5 by 20 cm., although they each contain 100 sq. cm. Also, the amount of scattering from a field which has a depth of 5 cm. is very different from that of a field of the same size but with greater or less depth. By indirect methods it is impossible to take all of these points into consideration, as can be done by the direct method.

It is obvious, then that the direct method of determining applied intensity is more accurate and is easier than any indirect method. It is probable, however, that the inaccuracies which exist when the indirect method is used do not influence the therapeutic results to a very great extent, and it is certainly preferable to use it than not to determine the applied intensity at all. It would seem to me that if anyone can go through the elaborate calculation required by the indirect methods in order to arrive at a conclusion as to the applied intensity, he would be even more capable of carrying out the direct method by means of a calibrated dosimeter, and would be aware of the factors which influence the method. One who is familiar with such details could certainly detect and correct inaccuracies in dosimeters, which are now constructed so that they are practically foolproof, and are provided with scales calibrated in "roentgens" so that the applied intensity may be read directly by timing the discharge rate with a stop watch.

This brings up the question, "How accurate should we be in estimating and applying radiation?" I am of the opinion that therapists should be as accurate as is practically possible. Too many therapists treat patients rather indifferently and apply only what the choose to call their own "standard erythema dose," irrespective of the condition of the patient, the size and shape of the field, or the disease for which the patient is being treated. This is fairly safe, but as a rule the patient does not receive the maximum benefit, and the therapist, as well as other members of the medical profession, is led by this negligence to become skeptical of the value of radiation therapy. Thus the radiolgist defeats his own ends. If we are ever going to be able to draw conclusions as to the biological effects of radiation we must measure the applied intensity and quality as accurately as possible in terms of established physical units.

It is stated frequently that too much attention is paid to the physical side of radiation therapy and physical mensuration, and that the medical side is neglected. Obviously, these statements are inconsistent because the present effort is to protect the patient and to attempt to understand the biological processes which take place in his tissues as a result of the application of a known quality and quantity of radiation, as well as to provide a common ground for the intelligent recording of methods and results.

The establishment of an accurate method of measuring dosage is an attempt to escape from archaic and haphazard methods of some who believe that they possess some mystic sense whereby they can predetermine specific indications, individual variations, radio sensitivity, and other reactions. Materia medica did not emerge from this same dark cloud of empirical therapeutics until physiological reactions were studied in relation to definitely known qualities and amounts of drugs. The grain, the gram and the *roentgen* are all exact physical units of measure.

Conclusions

1. On account of the variation in skin manifestations, the reaction of the human skin cannot be used as a standard for comparison of physical factors.

2. A unit of erythema cannot be divided to determine biological reactions nor can a unit erythema dose be used as a standard to indicate the response to a treatment which is not given at a single sitting.

3. The reaction of pathological tissues to radiation cannot be determined on the basis of a reaction of the normal skin.

4. There is no satisfactory biological standard for the determination of radiation intensities.

5. The only skin effect which is of importance is the average skin tolerance limit.

6. The direct method of measuring applied intensities is preferable.

7. The roentgen (r) is a practical physical unit of measure of applied intensity.