Chapter II

ROENTGEN DOSAGE

DEFINITIONS AND TERMINOLOGY

An understanding of the following terms aids in the proper study of the essential dosage factors.

Primary Radiation.—The primary beam of x-rays is the entire beam arising from the face of the target when the tube is in operation. The primary beam has its origin from that part of the focused cathode stream which strikes the face of the target of the tube.

Stray Radiation.—Some misdirected cathode rays striking various parts of the tube other than the face of the target produce x-rays and result in stray radiation. These stray radiations are of little or no importance in present-day therapy, as most of them are absorbed by the wall of the x-ray tube or other substance before they reach the patient.

Filtered Radiation.—The rays remaining in the beam after passage through some more or less dense material which was placed in their path to absorb the longer, less penetrating rays from the primary beam are known as filtered rays. Proper use of the various types of filters is extremely important in therapy.

Unfiltered Radiation.—The primary beam striking the patient without passing through any interposed material which absorbs some of the beam is called unfiltered radiation. Note well that unfiltered radiation is seldom used in any technic recommended in these pages; usually at least 1 mm. Al is used.

Scattered or Secondary Radiation.—Primary rays or filtered rays may strike objects in their path and rebound from these objects in any direction, even backward toward the target of the tube. The new rays resulting from such rebound are known as secondary or scattered rays and are of considerable importance in therapy. (See dosage measurement with and without back-scatter and the significance of the size of the port in relation to back-scatter.) Secondary radiation from equipment and from patients is a greater source of danger to x-ray operators and attendants than many of them realize or are willing to admit.

All sources of secondary radiation should be ascertained and adequate means of protection provided so far as it is possible to do so.

Characteristic Radiation.—Characteristic rays are rays peculiar to the metal from which they have their origin. They are present to some extent in all primary beams. Each of the various metals used in the manufacture of targets has some individual property which gives its beam certain characteristic rays by which the metal in the target can be identified if so desired by the expert physicist. If characteristic radiation is of any value in therapy, its application to the treatment of infection is not known to the writers and will not be considered.

The dosage factors in x-ray include all the selective adjustments of the equipment and its accessories which influence or describe the character of the primary beam of x-rays and its various modifications up to the termination of its action in the tissues. When given in full, they designate the interval between treatments, all the manipulations of the equipment under the control of the operator and the results obtained from them which have any bearing on the r unit production, dosage of x-rays in tissues or its subsequent loss. Thus dosage factors include in some instances the way and in other instances the result of the way in which the equipment is adjusted and the patient treated. Some comment on their clinical application in the various types of infections is made from time to time in the following pages.

When properly recorded, the dosage factors consist of a series of statements of facts concerning the essential relationships between the apparatus and the patient receiving the treatment and some estimations as to the probable amount of radiation absorbed by and then lost from the radiated tissues.

TABLE 1

TECHNICAL FACTORS

1. Kilovoltage.
2. Filter.
3. Milliamperage and time.
4. Distance.
5. Size of port.
6. r units per dose.
7. Space factor (or the time interval factor between treatments).
8. Total dose (factor) in a given period; maximum number of r units to be used for any one area in any given patient.
9. Loss factor; amount of radiation effect lost from the tissues in a given period of time.
10. Minimum and maximum intensity factors; lowest and highest percentage of radiation effect (tissue saturation) to be allowed during the course of treatment.

The first eight factors listed in Table 1 can be recorded as facts; the last two are at best estimations based on experimental data and previous clinical experience. They are accurate enough, however, to be of great assistance in the clinical application of radiation for acute infections and, with the other factors, make a complete record of the technic used in a given case. This record is essential when it seems advisable to use the same dose for another patient, to report to a colleague the technic used for a given patient and to study the technical factors used in a series of cases when searching for a possible change in dosage to improve results.

In a general way, these factors serve as a constant reminder that a specific amount of radiation must be given from time to time if any good is to be accomplished and, conversely, that some harm is bound to follow if too much radiation is given in too short a time.

The essential dosage factors will be more fully discussed from two angles, the technical and the clinical. An effort will be made to define each factor and then, by discussing its variations, to clarify the rôle it plays in the technical procedure and the clinical results. By this means the function of each as it is applied to the clinical problem of treating an acute infection may be more clearly understood and correctly applied. Included in this discussion are some extracts from the work of early investigators on the function of kilovoltage and filter in relation to absorption and to the absorption of radiation in relation to biologic effect.

KILOVOLTAGE

Technical and Clinical.—Kilovoltage is a term used to express electrical pressure or potential in thousands of volts. Anyone who is using the x-ray as a therapeutic aid must keep in mind that the primary beam is heterogeneous radiation as it leaves the target surface of the tube. It contains many different wavelengths, with the minimum length dependent on the kilovoltage used.

Early in the use of the x-ray, the term "soft" rays[8] was used to denote the rays of long wavelength and lesser power of penetration (produced by lower kilovoltage). Such rays are readily absorbed in the superficial tissues. The term "hard" rays meant rays of shorter wavelength having greater power of penetration (produced by higher kilovoltage). Hard rays deliver a greater dose to the deeper tissues. To state it more simply, the

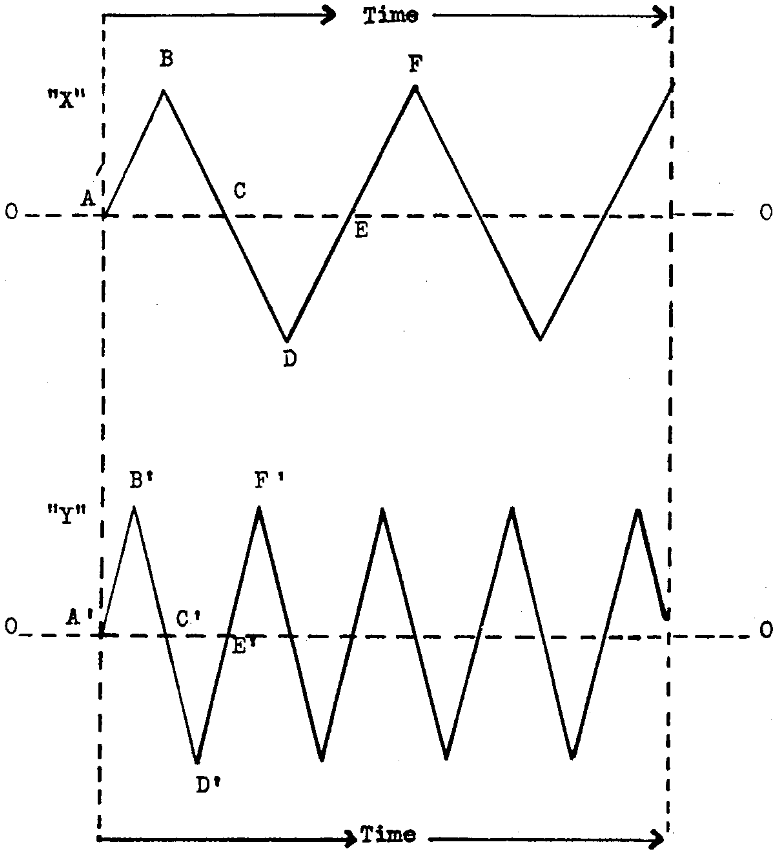

FIG. 2.—Graphic components of vibrations. The wavelength represented as *"X" (B-F)* is obviously longer than the wavelength represented as *"Y" (B'-F')*. A full cycle of any wavelength consists of a negative and a positive phase. Triangle *A, B, C,* above the zero line is the positive phase; triangle *C, D, E,* below the zero line is the negative phase. The wavelength may also be measured on the zero line as well as between the apexes of the crests of the waves. The distance from *A* to *E* on the upper zero line also indicates the wavelength of *"X"*, and is, therefore, equal to the distance *B* to *F;* this is obviously longer than wavelength *"Y" (A'-E')* on the lower zero line which in turn equals the distance from *B'* to *F'*. The number of vibrations represented in *"X"* and *"Y"* have occurred during the same length of time, and, therefore, the frequency is greater in *"Y"* than in *"X"*. Wavelength *"X"* is longer than *"Y"*, and is, therefore, produced by relatively lower voltage than that produced by *"Y"*, since the lower the voltage, the longer the wavelength of x-rays, and vice versa.

penetrating power of the x-rays depends on their energy. As this energy varies in inverse proportion to the wavelength (Fig 2), the higher the voltage, the shorter the wavelength and the more penetrating the ray; vice versa, the lower the voltage, the longer the wavelength and the less penetrating the ray.

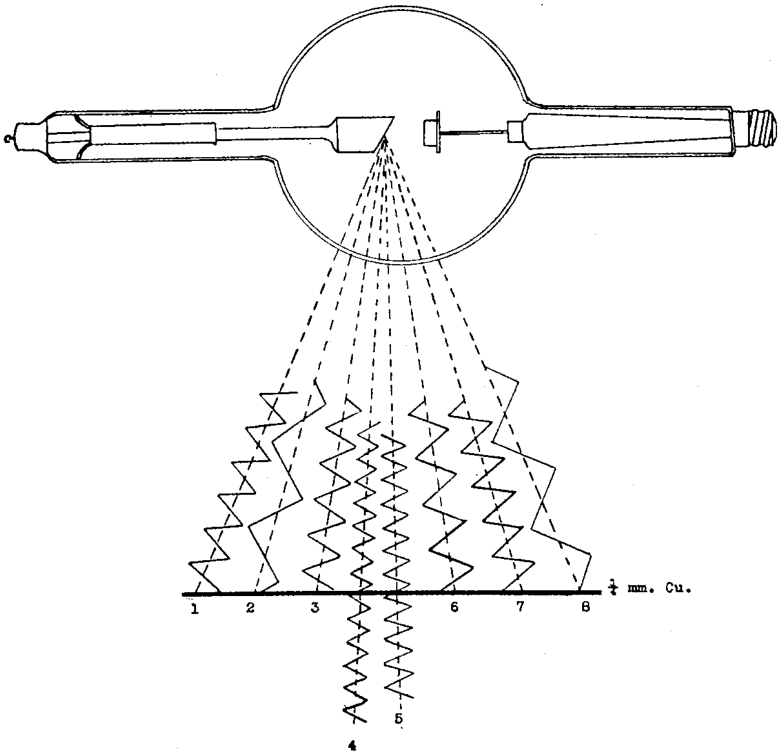

Fig. 3.—Primary beam with relatively large number of longer wavelengths produced by low voltage. The filter is represented as absorbing 75 per cent of the beam, allowing only the two shortest wavelengths *(4* and *5)* to pass through. The presentation is schematic, and it should not be presumed that any filter always absorbs 75 per cent of the beam. The amount of the beam absorbed depends on character of the primary beam and the material used for the filter.

Generally, the first factor of importance in selection of the type of rays to be used is the kilovoltage. The kilovoltage selected usually depends on whether the disease lies superficially or deeply in the tissues (Fig. 5).

Certain relatively opaque dressings over injured parts, such as casts over fractures, may be a cause for increasing kilovoltage.

Figures 3 and 4 represent two x-ray beams produced by different kilovoltage. Figure 3 shows the larger number of longer wavelengths with the lesser power of penetration in the beam generated with the lower kilovoltage. Figure 4 shows an increased proportion of shorter wavelengths with greater power of penetration in the beam generated with the higher kilovoltage. The primary beam (Fig. 5) shows x-rays of various wavelengths; the shorter (*1*) the more penetrating and the longer (*5*) the less penetrating. Since the shorter (*1*) passes entirely through the object and the longer (*5*) is absorbed in the skin, the intermediate wavelengths (*2, 3* and *4*) would obviously be more desirable for any infection involving the deeper tissues since they are absorbed in these areas.

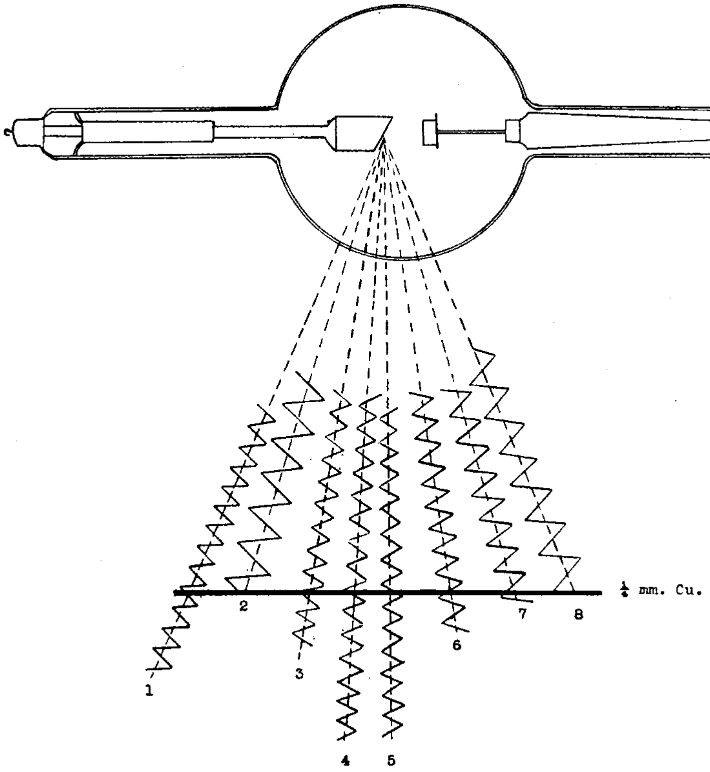

FIG. 4.—Primary beam with relatively larger number of shorter wavelengths produced by high voltage; the same filter as used in Figure 3 absorbs only 25 per cent of the beam because of the predominantly shorter wavelength produced by the higher kilovoltage.

As the kilovoltage is increased (Fig. 4), the relative number of the shorter wavelengths in a beam is increased; vice versa, as the kilovoltage is lowered (Fig. 3), a relative increase in the number of longer wavelengths is produced. Thus it is evident why one uses higher kilovoltages for infections which are deeply situated and the lower kilovoltages for the diseases limited to the superficial tissues, as shown diagrammatically in Figure 5.

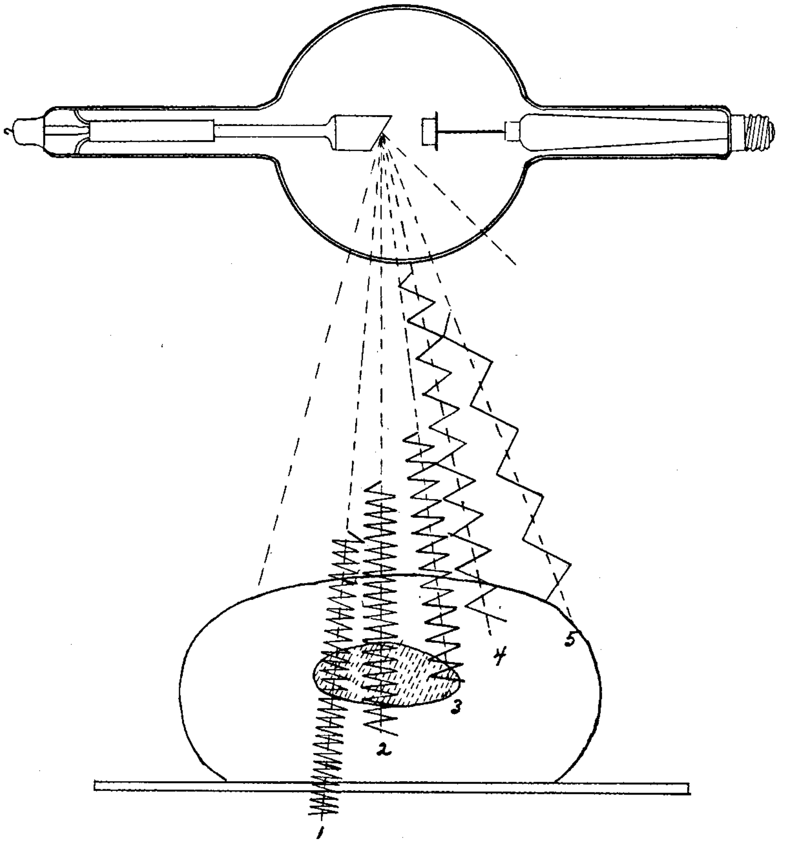

FIG. 5.—X-ray tube, primary beam of x-rays and an object representing tissues of two densities, such as a cross-section of the thigh absorbing various wavelengths at various depths.

It should also be kept in mind that as the kilovoltage is increased, although the wavelength for therapeutic purposes is shorter than before, unintentionally there is also a greater number of longer wavelengths produced. As a rule, for clinical purposes, these must be eliminated from the beam. This is usually done by increasing the filter as one increases the kilovoltage (Figs. 6, 7 and 8).

Figure 5 deals only with the quality of the x-ray, that is, the wavelength. To illustrate the significance of milliamperage (or volume), one might consider this beam quantitatively as one of five milliamperes. If one should increase the output to 10 milliamperes, i.e., double the milliampere output without changing any other factor, two wavelengths for each one now represented would be present in the new beam without affecting the proportion of either the long or the short wavelengths. Thus it is seen that increased milliamperage affects the beam only in relation to its quantity. Kilovoltage affects the beam primarily in the character (quality) of the rays produced, i. e., their wavelengths. Thus it is evident that by varying the time factor one is able to affect the quantity of radiation given, while by varying the kilovolts and the filter one is able to affect the quality of the radiation.

Historical Review.—The following excerpts concerning the qualities of radiant energy and the influence of resonance on absorption of light are from Bayliss' *Principles of General Physiology.*[9] They represent the contributions of several early investigators and are evidence of work done in the study of radiant energy some time before Roentgen's discovery of x-rays. They are fundamental and should be of interest to all radiologists because there is still so much to be learned concerning exactly what happens when cells, fluids, bacteria or their toxins are bombarded with x-rays.

Resonance

> Light consists of a series of periodic electromagnetic disturbances of various periods of vibration, or wavelength . . . . . When a system, such as a pendulum, has the same period of vibration as that of a series of minute impulses delivered to it, the system is set into a vigorous movement by the heaping up of the effects of a number of small impulses. It is, in fact, a means of accumulating energy. Consider now the effect of a set of various wavelengths, such as we find in the sun's light, on a chemical molecule, which has itself a definite rate of vibration. Some of the rates of vibration of the different light waves will almost certainly coincide with that of the molecules of the absorbing substance and will, therefore, set these into resonant vibration, which may reach an amplitude great enough to bring about chemical change. At the same time, those rays of vibration period in question

will be absorbed and, if situated in the visible part of the spectrum, there will be an absorption band seen by the eye. If in the ultra-violet, as in the case of many colorless organic compounds, the band, although invisible, may be photographed.[9]

Absorption of Radiation (Grotthus' Law)

Radiant energy, or radiation, is absorbed in tissues depending on the wavelength and the density and depth of the tissues radiated. Tissues are affected only by the radiation absorbed. This fact, known almost 100 years before Roentgen discovered the x-rays, was stated by Grotthus in 1819 and restated by Draper in 1841.

All substances absorb radiant energy to some extent: glass itself absorbs rays of longer wave length than those we know as light, and also those of shorter wave length. The colourless substance, anthracene, absorbs ultra-violet rays, and many other instances might be given. In other words, a part of the energy of a beam of light which traverses any substance is removed and held back in the substance. Something must, therefore, happen to the substance; it may be merely warmed, or other forms of energy may make their appearance in it, chemical or electrical change, and so on.

Grotthus' Law: It seems fairly obvious to us at the present time that no effect can be produced by light unless it is absorbed. We shall see presently also that some light energy must be used up to start any photo-chemical change, even when the reaction afterwards proceeds with evolution of energy. The law that light must be absorbed in order to produce an effect was first clearly enunciated by Grotthus (1819) and, independently, at a later date, by Draper (1841). It is frequently known as Draper's law.[9]

General Theory of Photochemical Action

We may take it then that light of some particular wave length is absorbed, and that it sets into resonant vibration the molecules of the absorbing substance, if any of the vibration periods of the light waves coincide with those of the latter. What is the further course of events? We know that, in many cases, chemical reaction follows.[9]

The method of measuring the amount of radiation absorbed by various substances by determining the amount of light remaining in the emerging beam, as suggested by Roscoe and Bunsen in 1855, is of interest because it has a direct parallel in our method of determining the quality of an x-ray beam by its half-value layer. This is the method of measurement preferred by some and accepted by all (p. 34).

The Laws of Lambert and of Beer

In order to be able to compare the amount of light absorbed by one substance or solution with that absorbed by another, it is necessary to take some standard of measurement. Bunsen and Roscoe (1855-1859) introduced the extinction coefficient for this purpose.

When light of a particular wave length is absorbed by any substance, it is clear that the intensity of the light issuing from it is less than that which enters it, and that there must be some particular thickness of it which reduces the intensity of the light to one-tenth of the value it had on entering. In order that the numbers characteristic of different substances should rise or fall in the same direction as the absorbing power of the substance or solution, Bunsen and Roscoe defined the extinction coefficient as being reciprocal of the depth of the solution required to reduce the intensity of light of a given wave length to one-tenth of that which it had on entering. It is plain that the greater the absorbing power, the less the depth required; hence the advantage of the inverse value, the extinction coefficient being directly proportional to the absorbing power.[9]

Measurement of Quality (Half-Value Layer)

Concerning the measurement of quality, Hudson said:

> Two methods of determining such a wave length are in common use today. One is the determination of the half-value layer, that is the thickness of some standard substance, such as copper or aluminum necessary to reduce the intensity of the radiation to one-half its original value. From this value, one may secure an absorption coefficient, and assuming a definite relation between absorption coefficient and wave length, an average wave length can be determined.[6]

It is recommended by the International Committee for Radiological Units (Chicago, 1937) that aluminum be used with 20 to 120 kv. and that copper be used with 120 to 400 kv.

Clinical Application.—For clinical purposes, sufficient kilovoltage must be used to deliver the proper quality of x-rays to the involved area. At present it appears this will vary from 70 to 140 kv. for acute infections. In the early experience of one of us in treating gas gangrene, the first two patients with involvement of the trunk were lost because of inadequate kilovoltage. After that experience, higher kilovoltage was used in treating infections in the trunk. As a result, in the second series,[10] no patient with trunk involvement died.

A range of 70 to 140 kv. has been suggested. Although we have records of patients treated successfully with kilovoltages above and below that range, we feel that too low a kilovoltage might result in unnecessary loss of life and a kilovoltage around 200 with 0.5 to 1 mm. Cu filter produces slower response in an infection of an extremity than does the lower voltage.

If 100 or 140 kv. will do, higher kilovoltages should be avoided owing to the slow response and the danger of serious sequelae if there is a miscalculation of dosage. From 70 to 100 kv. will do for the usual case involving an extremity, and 100 to 140 will do for an infection of the trunk.

In our first report, we recommended two relatively small doses each day for three to five days. Believing that the two patients with infection of the trunk were lost because of inadequate kilovoltage, we recommended sufficient kilovoltage in the future to deliver an effective depth dose. Despite this recommendation, we received in the mail recently (almost nine years after the first report) a detailed report of the x-ray treatment of a gas bacillus infection of the abdomen. Only 65 kv. had been used, and the patient died. The physician was anxious to know why the patient died. Reports on the treatment of trunk infection plainly stipulated kilovoltages above 100, depending on the size of the patient.

Because kilovoltage is an important factor in determining the quality of the radiation,[11] it is important to select the kilovoltage producing the rays most likely to be absorbed in the area treated. We have found the response of a gas bacillus infection of the extremity to 200 kv. and 0.5 mm. Cu not as prompt or definite for the same number of r units as the response when 90 kv. and 1 mm. Al were used. This, however, is strictly a clinical opinion regarding a matter on which some research is needed. When the infection is chronic and superficial (tuberculous glands), over-penetration with high voltage and heavy filtration can lead to bronzing, fibrosis and lowered resistance to secondary infection, and still fail to secure the maximal beneficial effect.

The selection of the proper kilovoltage is extremely important. If in doubt, one should always err on the side of the heavier voltage, since to select too low voltage may cost a life.

FILTER

Technical and Clinical.—Filter is a substance used to change the quality of a beam of radiation by absorbing the longer, less penetrating rays and allowing only the shorter, more penetrating rays to reach a given area of tissue.

Any primary beam of x-rays, whether predominantly hard or soft, is of a heterogeneous type and is less easily managed in clinical work than a beam of a more homogeneous type. This difficulty in the management of the heterogeneous beam is due to its greatly unbalanced rate of absorption in the various layers of tissue because of the large proportion of longer, less penetrating rays.

In the original heterogeneous, unfiltered state, the excessive number of longer wavelengths would be absorbed in the superficial layers of tissue. An undesirable reaction would take place in the skin before a sufficient number of the shorter wavelengths could reach the deeper structures to secure the desired effect at the greater depth.

Some means of rendering this heterogeneous beam more nearly homogeneous is necessary to secure uniformity of its rate of absorption in the various layers of tissue. Different types of filter are used to eliminate from the primary beam the undesirable longer wavelengths. The remaining filter beam is still heterogeneous, but is much less so than formerly, and as a result it is more manageable in its clinical application.

To increase the rate of absorption in the superficial tissues, lighter filters should and will be used, all other factors remaining the same. To increase the rate of absorption in the deeper tissues, the heavier filters should be used. As the filter is increased, the depth effect is increased. Therefore the amount of absorption desired in any plane of tissues varies with the condition to be treated and is dependent on the kilovoltage employed as well as the filter and the size of the port. As a general rule, more filter is added as the kilovoltage is increased, but the requirement of each case determines whether or not this rule is to be followed.

The second technical factor of clinical importance is, therefore, the selection of the proper filter (Erskine[12]) which, in proportion to its amount and its density, eliminates from the primary beam the longer wavelengths which are undesirable when in excess. The proper filter governs the rate of absorption of the rays in the various layers of tissues, tending to make the absorption more uniform and less dangerous to the patient, in that all tissues are radiated with more nearly equal effect. The safety factor is thus increased by the use of proper filters, and also maximal therapeutic response is assured. (See Figs. 6, 7 and 8.)

Since the ability of the x-rays to penetrate opaque objects is in inverse proportion to the density of the object, filters of heavier metals eliminate more of the longer wavelengths from a beam than do filters made of the same thickness of a lighter metal.

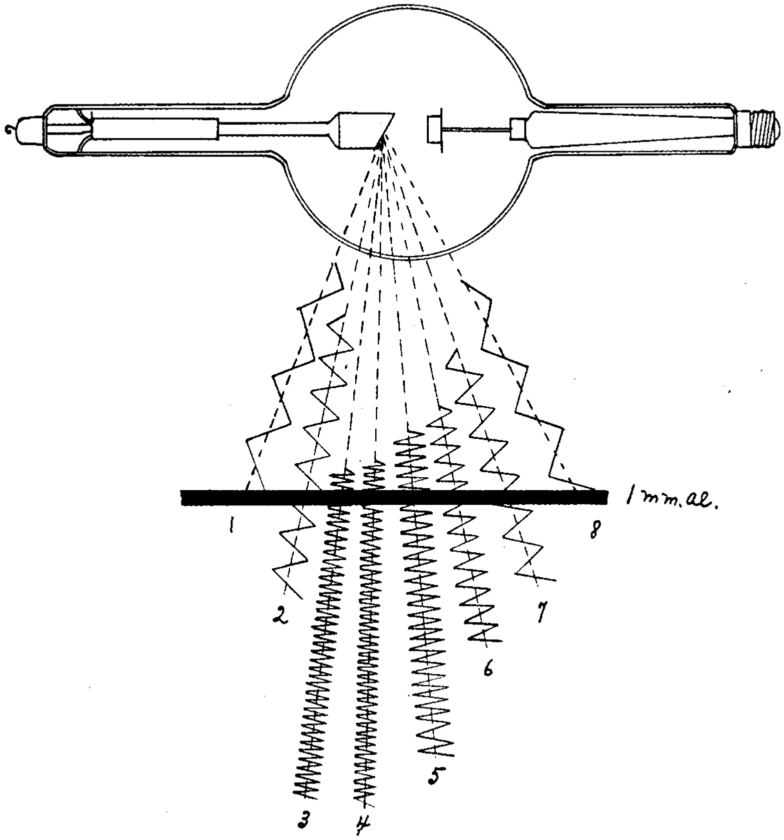

FIG. 6.—Function of filters. Primary beam of radiation produced by same kilovoltage as primary beam in Figure 7. The 1 mm. Al filter absorbs only the very long wavelengths.

A comparison of the filter values of aluminum and copper of equal thickness is shown in Figures 6 and 7. The longer wavelengths (*1, 2, 6, 7* and *8*) are eliminated to a greater extent by copper than by the same thickness of aluminum, which absorbs only *1* and *8*. This fact has been the basis for the preference during the past several years for copper rather than aluminum in higher voltage therapy.

A combination of two or more metals, such as aluminum, copper, zinc and tin, has been found to have an added clinical advantage over any single metal that can be used for filters.

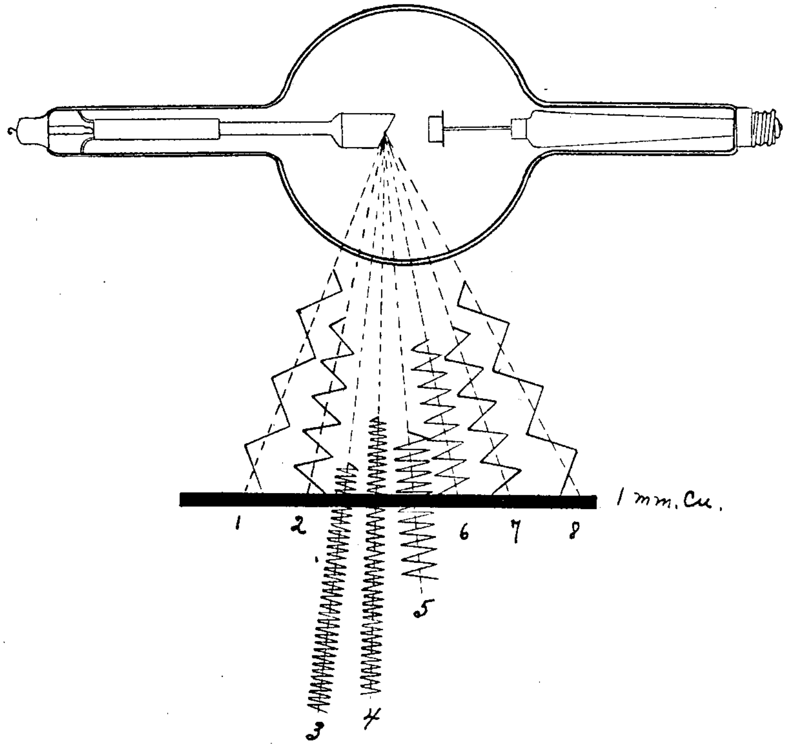

FIG. 7.—Function of filters. Primary beam of radiation produced by same kilovoltage as primary beam in Figure 6. The 1 mm. Cu filter absorbs all but the shortest wavelengths. The filtered beam emerging from the copper is more homogeneous than the beam emerging from the aluminum.

The function of additional filter is illustrated in Figure 8, which shows increased absorption of the longer wavelengths with each increase in filter. In the first layer of filter, the longest rays (*1* and *10*) are absorbed. The next longest (*4* and *9*) are eliminated in the second layer; *2* and *7* are absorbed in the third layer, and the four shortest wavelengths (*3, 5, 6* and *8*) pass through all layers of the filter material. It will also be noted that the heterogeneous character of the primary beam becomes less heterogeneous as it passes through each layer of filter. It is relatively homogeneous as it emerges from the filters for use in the tissues.

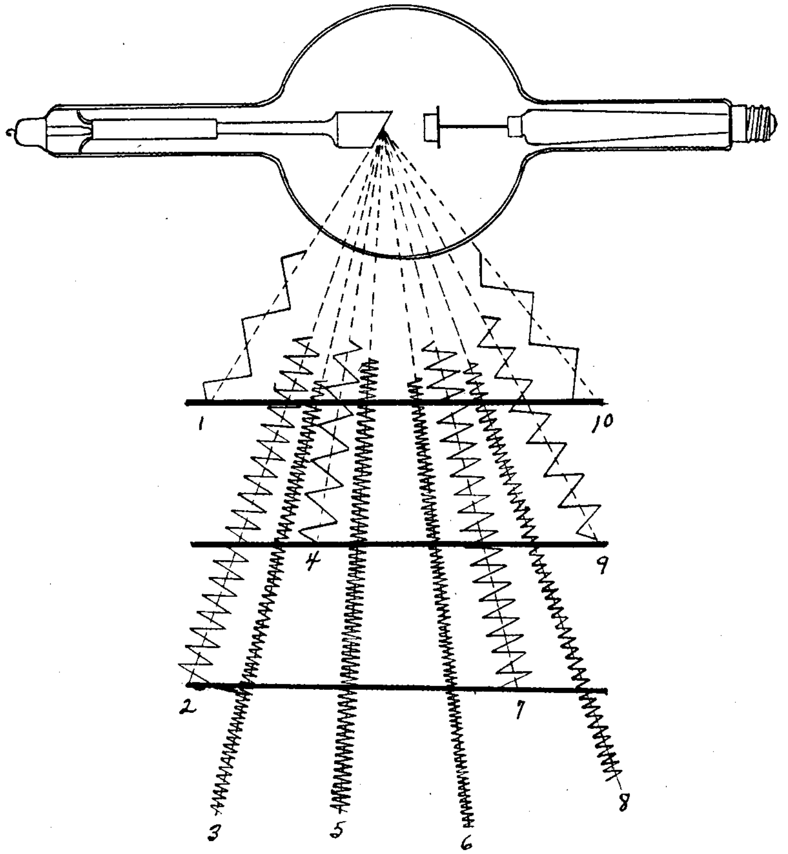

FIG. 8.—Function of additional filter. Each increase of filter absorbs additional wavelengths until the resulting beam is homogeneous although much reduced in volume.

The law of Grotthus concerning the action of radiant energy in tissues far antedated Roentgen's discovery, but it is still applicable. The fact that the radiant energy must be absorbed to produce an effect necessitates some consideration of the quality of the radiation used in the tissues. Obviously, therefore, one should not use the higher voltages and heavier filtration to treat an inflammatory lesion, because relatively small amounts of energy are absorbed in the tissues when produced by such factors as compared with lower voltage and lighter filtration. Early experiences made it evident that heavy doses are not needed for the treatment of acute inflammations. They do not require the prolonged and intensive treatment one must give a neoplastic process; in fact, quite the opposite is true. Apparently only a small amount of radiant energy is uniformly absorbed in the tissues at short intervals of time, for only a few days will produce the therapeutic effect desired in the infected tissues.

One sees in the literature reports of series of cases in which treatment was more or less successful with a great variation of technical factors. If one were to assemble all these data, with no clinical experience as a guide, one might be inclined to believe that one set of factors will do for all diseases or that any technic is as effective as another in the treatment of infections. Such is not the case. The best technical procedure has probably not yet been definitely determined for any of the diseases successfully treated at the present time; but Grotthus' law and clinical observation clearly indicate the incorrectness of just any procedure. Whether the action or response in the tissues radiated is thermal, chemical or electrical is not known, but the degree of absorption of the radiant energy in the tissues does determine the effect the radiant energy exerts in the cells. All radiologists know from everyday experience that relatively slight changes in kilovoltage, thickness of the part and distance definitely affect the amount of radiation absorbed by the tissues. This difference in the degree of absorption is shown by the amount which passes through and registers on the film or fluoroscopic screen.

It is probably true that the selection of therapeutic factors need not be as exact as the selection of diagnostic factors to obtain a satisfactory result, but this comparison of therapeutic and diagnostic factors leaves one with the idea that, as in roentgenography so also in therapy, there is a set of factors which is most efficient and most desirable. Although the range of factors for a satisfactory therapeutic effect is undoubtedly broader than that permitted in roentgenography for a satisfactory effect, the technic of choice for roentgen therapy has its limitations; above or below this, poor results will be obtained.

With the foregoing facts in mind, the problem is to select the proper technical factors which permit the greatest amount of absorption with the least tissue damage to overlying structures; which may be given once or twice daily over a three to six day period, and which clinical experience has shown to have had a favorable effect in a given type of acute infection.

Seldom have we recommended any therapy for any infection without the use of filter. The absence of filtration may warrant criticism of this type of therapy, and its omission in treating any infection is unwise. The writers commonly use from 1 to 5 mm. Al; occasionally 0.25 mm. Cu and 1 mm. Al; rarely 0.5 mm. Cu and 1 mm. Al. Previously it was stated that the more superficial the lesion, the lower the kilovoltage and the lighter the filter; conversely, the deeper the lesion, the higher the kilovoltage and the heavier the filter.

Figures 6, 7 and 8 are graphic representations of the function of filters, but, as is the case with other technical factors, the selection of filter in each instance must be individualized.

Variation in the dosage factors indicated in Table 1 is necessary as one approaches the limit of skin toleration or it is evident that treatment must be continued beyond the time and the number of doses originally planned. As the radiation effect accumulates in the tissues above the maximum intensity usually required for the type of infection being treated, it is customary to increase the filter, probably at the same time reducing the number of r units from that given during previous treatments. To compensate for these two changes made to avoid an undesirable skin effect, the kilovoltage may be raised slightly, usually not over 10 kv.

In the subacute and chronic infections, changes in the filter may be necessary to prolong the time and increase the dose. As a general rule, the longer the total period of time required to treat what is usually an acute infection, the more filter must be used. It is also a general rule that the deeper the disease, the greater the kilovoltage and the heavier the filter.