

ARCHIVES OF THE ROENTGEN RAY  
RADIOMETRY.

By DR. TH. CHRISTEN, Berne.

THERE are two distinct measurements in radiology, *viz.*, the *quality* and the *quantity* of the rays. More exactly, we may say that it is necessary to measure both the *penetrating power* and the *radiant energy*.

It is of the utmost importance not to confound these two questions, an error which is often made, and is still met with even in recent literature. For instance, it is often proposed to define the penetrating power of a radiation by the number of millimetres of aluminium which it will penetrate. But it is easy to understand that the number of millimetres penetrated will increase, not only with increase of the penetrating power, but also with the increase of the energy, or intensity of radiation.

In order to separate the question of penetrating power from that of intensity, we must always consider the *percentage* of the incident energy passing through the absorbing substance, not the absolute quantity. If, for instance, a given layer lets through nearly the whole incident radiation, the penetrating power of that particular radiation for the absorbing material is nearly 100 per cent. If, on the contrary, the radiation is almost completely absorbed, its penetrating power approaches zero. There are all degrees of penetrating power between these two extremes, and the object of this article is to establish a measure of penetrating power which shall be sufficiently accurate for practical use, and entirely independent of the intensity of the radiation.

The percentage of radiant energy penetrating a layer of absorbing material depends on three factors:

1. The penetrating power (or hardness) of the rays.
2. The nature of the material penetrated.
3. The thickness of the absorbing layer.

To simplify the problem we eliminate the second factor by choosing *water* as the standard for all our measurements. In actual experiments we may either use water itself or any other substance which has the same absorbing power.

In measuring the absorption, we find that it is simpler in practice to determine the thickness which will absorb a given percentage, than to determine the varying percentage absorbed by a stated thickness of the material under examination. For simplicity, we have arbitrarily chosen 50 per cent as the standard absorption. The penetrating power of the radiation is therefore measured by the thickness of that layer of water which absorbs just 50 per cent. of the incident energy, and lets the other 50 per cent. pass through.

*The HALF-VALUE-LAYER for a given radiation is that thickness of water which, by absorption, reduces the energy of the incident radiation by exactly one-half.*

It is easy to see that this measure of the penetrating power depends in no way on the intensity of the radiation. One radiation may be a hundred times more powerful than another, but if the same layer of water reduces each by 50 per cent., the penetrating power of the two radiations is the same.

Hence the *half-value-layer* is an exact measure of the penetrating power, entirely independent of the intensity of the radiant energy. The "harder" the radiation the greater its penetrating power, and the thicker its half-value-layer.

HOMOGENEITY AND HETEROGENEITY.—The measurement of radiations by the half-value-layer is of great advantage when dealing with the question of homogeneity, and even gives us some assistance in determining the degree of heterogeneity of any radiation.

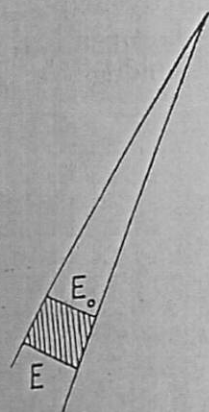


Fig. 1

And, firstly, as to *homogeneous* radiations. We know that a homogeneous radiation is absorbed according to an exponential formula. If  $E_0$  is the quantity of incident energy and  $E$  the energy passing through the absorbent layer of thickness  $x$ , we have :

$$E_0 = E.e^{a.x} \quad (1)$$

wherein  $a$  is the co-efficient of absorption (see fig. 1) and  $e$  the base of the Naperian logarithms.

If  $a$  be the half-value-layer, we know that for this layer (*i.e.* when  $x = a$ )  $E_0$  will be twice  $E$ . Therefore :

$$2 = e^{a.a} \quad (2)$$

or

$$a.a = \text{nat. log. } 2. \quad (3)$$

Finally, the formulæ (1) and (3) give

$$E_0 = E.2^{\frac{x}{a}} \quad (4)$$

We see that the exponential formula may be written in two forms, either (1), which contains the co-efficient of absorption as a characteristic, or (4), which is based on the conception of the half-value-layer,  $a$ . The relation of these two quantities is given by the formulæ (2) and (3).

All this is easy to understand. It is less difficult to form a concrete idea of a half-value-layer measured by centimetres than of a co-efficient of absorption which is a mathematical abstraction measured in  $\text{cm}^{-1}$ . This is why we prefer to use the half-value-layer for practical purposes.

The difficulties, however, increase greatly when the radiation considered is no more homogeneous. We are, however, bound to study the question of non-homogeneous radiations, because the radiations employed in radiography and radiotherapy are all compound and often vary greatly in their composition.



To treat the question of the penetration of such a beam by the co-efficients of absorption becomes very complicated. The formula for the absorption of a heterogeneous radiation is given by

$$E = E_0 \cdot \frac{b_1 \cdot e^{-a_1 \cdot x} + b_2 \cdot e^{-a_2 \cdot x} + b_3 \cdot e^{-a_3 \cdot x} + \dots}{b_1 + b_2 + b_3 + \dots} \quad (5)$$

The question becomes much simpler if we employ the graphic method. Fig. 2 shows the absorption of a homogeneous radiation whose half-value-layer is  $a$ . The thicknesses of the absorbing layer are shown as abscissae, and the corresponding intensities as ordinates. We notice that the half-value-thicknesses are everywhere equal. The horizontal distance between 100 per cent. and 50 per cent., between 60 per cent. and 30 per cent., and between 50 per cent. and 25 per cent., etc. are each equal to  $a$ .

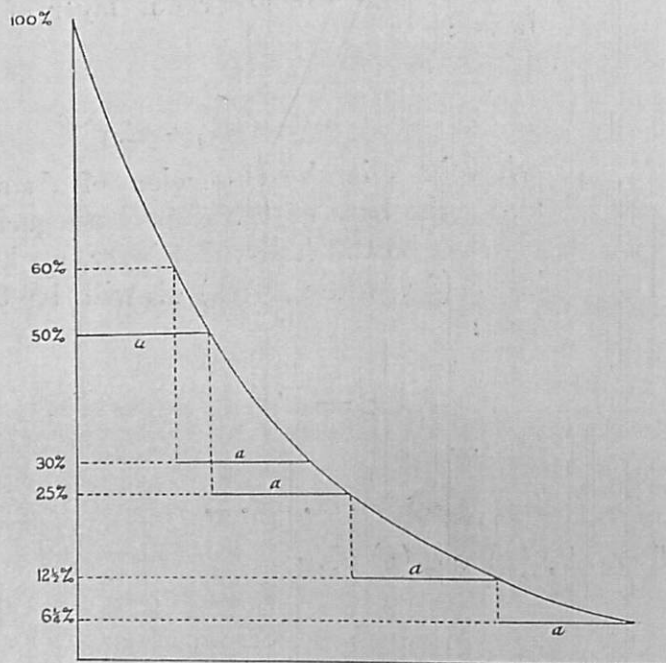


Fig. 2

Absorption of a Homogeneous Radiation.

The absorption of a non-homogeneous radiation shows a very different graph. The reader will remember the law of Roentgen,\* that every additional layer of absorbing material increases the average penetrating power of the X-ray beam. This law of Roentgen may also be stated as follows:—*The deeper the X-ray beam penetrates into any absorbing material, the greater is its half-value-layer.*

We shall now consider Fig. 3, which represents the absorption of a non-homogeneous radiation, composed of two homogeneous beams, whose half-value-layers are respectively  $a^*$  and  $a^{**}$ . The first half-value-layer of the

\* It must be understood that, although the law of Roentgen may be explained by the heterogeneity of X rays, this is not the only possible explanation. There may be—and probably are—still other causes for the increase of the penetrating power by increasing the thickness of the absorbing layer.

compound radiation is the difference between 100 per cent. and 50 per cent.; it is marked,  $a_1$ . From 50 per cent. to 25 per cent. we get the second half-value-layer,  $a_2$ . We see at once that  $a_2$  is greater than  $a_1$ . The third half-value-layer,  $a_3$ , between 25 per cent. and 12.5 per cent. is still larger than  $a_2$ , and so on.

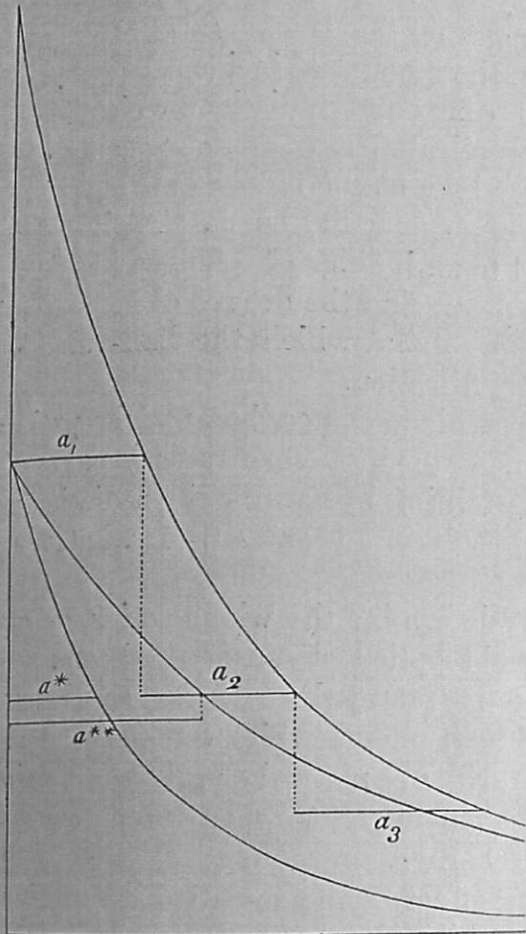


Fig. 3

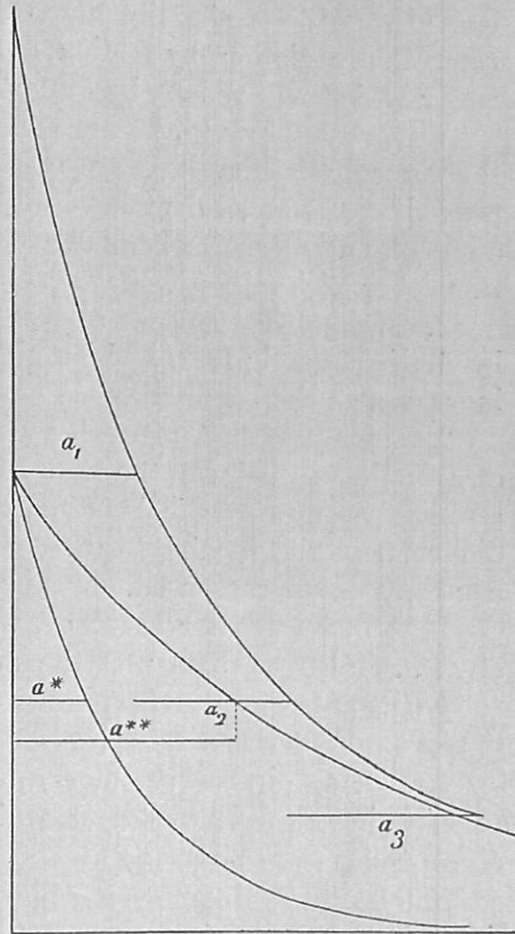


Fig. 4.

Absorption of a Non-homogeneous Radiation.

The ratio of  $a_2$  to  $a_1$ , we call the *index of heterogeneity*,  $h = \frac{a_2}{a_1}$ . In any homogeneous radiation  $h$  is equal to unity, whereas the more heterogeneous the radiation the greater will be the value of the index  $h$ . Take for instance Fig. 4. Here the two components of the compound radiation differ much more than in Fig. 3, *i.e.*, the difference between  $a^*$  and  $a^{**}$  is much greater in Fig. 4 than in Fig. 3. If we find the value of  $h$  in each case, we get  $h = 1.05$  in Fig. 3, and  $h = 1.2$  in Fig. 4.\*

\* It might, perhaps, be better to choose the ratio  $\frac{a_3}{a_1}$  or even  $\frac{a_4}{a_1}$  as the index of heterogeneity instead of  $\frac{a_2}{a_1}$ . Time and experience alone can show which ratio is of most practical value. The principle is the same whichever is used.



We thus see the double advantage of the half-value-layer measurement. 1. With a non-homogeneous radiation we can no longer speak of "the co-efficient of absorption," because there are an indetermined number of such co-efficients, each component of the beam having its own different value. But every radiation, however heterogeneous, always has a half-value-layer. We cannot, indeed, apply formula (4) above to the heterogeneous radiation, but we can always determine its half-value-layer, whatever the composition of the compound radiation, by finding experimentally the thickness of that layer of water which will reduce by 50 per cent. the amount of incident energy.

There may, indeed, be an infinity of compound radiations which have all the same half-value-layer, just as a complicated sum of components cannot possibly be expressed without ambiguity by a single figure, but this objection applies to all other methods of measuring a compound beam. A given degree Benoist or Wehnelt, etc., may correspond to an infinity of compound radiations.

2. The half-value-layer allows us to determine the degree of heterogeneity by finding the index  $h$ , which gives the rate at which the half-value-layer increases as the beam becomes harder by filtration.

This index of heterogeneity  $h$  is of great importance, because the problems of radiotherapy point to the need of the most homogeneous radiations possible, and it gives us a practical method of determining by how far the radiation used differs from the ideal. In the *ideal* homogeneous beam  $h = 1$ , whatever the hardness of the rays used.

If we need greater accuracy, we can determine the whole series,  $a_1, a_2, a_3$ , etc. . . . and from them plot the entire absorption curve of the beam.

I will not abuse the hospitality granted to me by the Editor of the ARCHIVES to repeat the description of the different instruments which have been devised for measuring directly the half-value-layer. Let me rather give the details of an experiment, easy to repeat, which seems to me to change somewhat our views about the so-called "filtration" of X rays.

One used to think that the hardening effect of the so-called "filters" consisted in the absorption of the soft rays whilst the hard rays were allowed to pass through unchanged. But we should not forget that we can never retain *all* soft rays or let *all* the hard ones pass. We can only arrest within the filter the majority of soft rays and let pass a relatively large proportion of the hard rays, thereby increasing the proportion of hard rays in the compound radiation. The name "filter" is an unfortunate one, since the action of the "filter" of the radiologist differs fundamentally from that of the "filter" of the chemist. The latter must completely retain all precipitates and let pass completely every fluid.

These "filters" are most used by radiotherapists. They eliminate the softer components of the compound radiation, or, to judge, we say the radiotherapists want to "harden" their increase their penetrating power. We must, however, try to express more exactly; we should know how much we increase the per or the half-value-layer.

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The filters most used are sheets of aluminium, varying in thickness from one to several millimetres. We have also used aluminium for measuring the penetrating power of the rays, taking the absorbing power of aluminium as 10 times greater than that of water, *i.e.*, 1 mm. of aluminium absorbs as much unfiltered rays as 10 or 11 mm. of water.

But this ratio no longer holds good for rays which have passed through several millimetres of aluminium. To be convinced of this it will be sufficient to test the photographic action: we find that X rays, filtered through 3 mm. of aluminium, are equally absorbed by 1 mm. of aluminium, and by 7 or 8 mm. (instead of 10 or 11 mm.) of water. It follows that *the filtering of X rays through 3 mm. of aluminium increases their penetrating power for water 30 per cent. less than their penetrating power for aluminium.*

Now the majority of hardness-scales (Benoist and its modifications by Walter and Wehnelt) are based on the absorption of the rays by two sheets, one silver and the other aluminium. The rays filtered through 3 mm. of aluminium have, however, gained in penetrating power, particularly for aluminium. This makes an exceptionally clear field behind the aluminium of the scale, and thus the penetrating power is estimated too high.

For this reason I use artificial amber or bakelite for all my scales, instead of aluminium, because this material has about the same absorbing power as water.

Moreover, we must recognize that there is no such thing as a simple "filtration"; we must think of it as a kind of selective absorption. But for this we must assume a very large number of "colours," so that any selective absorption should diminish the intensity much more than it actually does. This is why I proposed to discard the word "filter" and use "transformator" or "hardener" instead, saying that absorbent materials "harden" the rays, not "filter." Perhaps we may, in time, discover the true nature of this hardening process.

**DOSAGE.**—The problem of dosage is far more difficult than the measurement of penetrating power. The dose is not the quantity of radiant energy impinging on a surface, but the *energy absorbed by unit volume*. With a given quantity of energy hitting a surface, the amount of energy absorbed under this surface depends still on the penetrating power of the rays, for the more penetrating the rays the less they are absorbed, and the smaller will be the dose. If it were possible to produce such ultra hard rays, that they would not be absorbed at all, their biologic action would certainly be nil.

Further, there must enter into our arguments the *time*, for we may get the same quantity of radiant energy absorbed by a feeble radiation as by another three times more powerful, provided that the former is acting for three times as long.

For the sake of brevity we use the term "intensity" for the quantity of radiant energy impinging on unit surface in unit time. If  $E$  be the incident



energy, T the duration of irradiation, S the area of the irradiated surface, and I the intensity :

$$I = \frac{E}{S.T} \quad (7)$$

or

$$\frac{E}{S} = I.T \quad (8)$$

This fraction  $\frac{E}{S}$  plays a rather important rôle in radiometry, it has been given the name surface-energy (Flächenenergie), and is designated by the letter F. From formula (8) we see that this quantity F will have the same value for small intensities lasting a long time as for great intensities of short duration, provided that the product I.T be of constant value. The same result is seen in photography: with a light ten times as powerful we must expose for only one tenth of the time to obtain the same photographic effect.

What is it, then, that all our dosimeters measure, whether Sabouraud, Bordier, Kienböck, Schwarz, etc.? Is it this surface energy? At first sight we should say yes, for all these test bodies measure the product of intensity and time, since their colour changes with the intensity and the time of exposure. But this cannot be true, for with the same quantity of radiant energy much more is absorbed when the rays are softer. And we know that the rays passing through it do not change the colour of the test body, but only those absorbed.

Considering our most usual test bodies, we find that there is always quite a thin layer, the colouration of which indicates the quantity of radiant energy absorbed. If we calculate the amount of absorbed energy from formula (4) we get

$$E_0 - E = E. \left(2^{\frac{x}{a}} - 1\right) \quad (9)$$

and since  $x$  is very small, we may put

$$2^{\frac{x}{a}} - 1 = \frac{x}{a} \log. 2 \quad (10)$$

an equation to be found in every text book of analysis. From (9) and (10) we find that the energy absorbed by a thin layer, whose thickness is  $x$ , has the value

$$E_0 - E = E. \frac{x}{a} \log. 2 = \frac{x}{a} 0.7 \quad (11)$$

Since the area of the surface irradiated is  $S$ , the absorbing volume will be  $S \cdot x$ . The dose  $D$ , which we have defined as the quantity of radiant energy absorbed by unit of volume, must be

$$D = \frac{E_0 - E}{S \cdot x} \quad (12)$$

hence from (11) and (8)

$$D = \frac{E}{S \cdot a} 0.7 = \frac{F}{a} 0.7 \quad (13)$$

That is to say: *The dose is equal to seven tenths of the surface energy divided by the half-value-layer of the given radiation.* (It is evident that this formula is rigorously applicable only to homogeneous radiations.)

I will not fatigue my readers by further details. All these questions are thoroughly treated by my book, "Messung und Dosierung der Roentgenstrahlen." I will only mention the following results:

With homogeneous rays of given intensity the maximum dose at a depth  $p$  is obtained when the rays are of such hardness that their half-value-layer is  $7p$ . With a heterogeneous beam of the normal type used for radiotherapy the maximum dose at a depth  $p$  is obtained when the half-value-layer equals  $p$ .

This means that in order to make the best of the radiant energy available for deep radiotherapy, we should choose rays of such penetrating power that their intensity will be reduced by one half by a layer of water equal to the thickness of the superposed tissues. The deep dose will then be approximately equal to one half of the surface dose. (I say "approximately" because by passing through the superposed tissues the penetrating power of the rays increases somewhat, whereas the dose decreases.)

Biological experiments have confirmed the predictions of those theoretic results: The more we could increase the penetrating power of the X rays, the more successful was our deep radiotherapy. The limit  $a = p$  has not yet been attained for deep-seated organs, such as the ovaries. We hope, in the near future, to have at our disposal still harder rays. I do not doubt that the biologic effect will again diminish as soon as the penetrating power is increased much beyond  $a = p$ .

Further, it is important to know whether our test bodies really measure the dose independently of the penetrating power. Here we must remember that all these test materials do not have the same absorbing power as the tissues. We must, therefore, denote their half-value-layers, not by  $a$ , but by another letter, say  $a^*$ . These test bodies, therefore, do not measure the dose for the tissues,

$$D = \frac{F}{a} 0.7 \quad (13)$$



but another "dose"

$$D^* = \frac{F}{a^*} 0.7 \quad (14)$$

from which we deduce

$$D = D^* \cdot \frac{a^*}{a} \quad (15)$$

There remains a big question to be solved: Is the quotient  $\frac{a^*}{a}$  constant for all possible rays of every penetrating power? If so, there would be no need of a correcting factor. To judge from recent publications one might not be inclined to believe it is so, except for the air, which has to be considered in all instruments based on ionisation, such as those of Szilard and of Grossmann. But all these questions have not been sufficiently examined to allow us to give a definite judgment. However, as soon as we are in possession of any test body whose index  $\frac{a^*}{a}$  is constant for all half-value-layers, that test body will measure the dose independently of the penetrating power. We owe to Professor Szilard one most excellent idea, the reduction of our radiological dosage to well-known quantities of energy. Szilard has proposed to define the unit of dose by the number of ions set free by a given irradiation. If I be allowed to complete this definition, I should say that the dose should be measured by the number of ions set free in one cubic centimetre of air. It seems absolutely necessary to make this addition, since we have already defined the dose as the amount of energy absorbed *by unit volume*.

Therefore, following Szilard, and taking the mega-mega-ion, *i.e.*  $10^{12}$  ions as the unit, we define the unit of dose as  $10^{12}$  ions absorbed by 1 c.c. of dry air at  $15^\circ$  C. and at normal atmospheric pressure.

I do not doubt that this idea of Szilard will prove very useful, and I should like to propose that we call the new unit, the mega-mega-ion, a "Szilard." The only question is whether it would not be better still to calculate the amount of energy, in ergs, that is required to set free  $10^{12}$  ions. The unit of dose would then be expressed by ergs per cubic centimetre.

In order to find the dose for the tissues, we must multiply the dose Szilard by the ratio of the half-value-layers of air and of water respectively. This ratio is assumed by Szilard to be 800, *i.e.* one inch of water absorbs as much radiation as 800 inches of air. It still remains to be shown whether this figure is sufficiently constant, or whether any correcting factors must be applied, particularly for radiations of high penetrating power.

It follows from these arguments that no test body whose index  $\frac{a^*}{a}$  changes in value for rays of different penetrating power can be used for measuring the dose without applying to it certain corrections, as yet undetermined. Grossmann has shown that above a certain penetrating power the half-value-layer for silver decreases, whereas that for water increases. Here the quotient  $\frac{a^*}{a}$

must show a sudden and considerable decrease. This fact explains the incredibly high number of Kienböck units which some radiotherapists are reported to have given without danger.

There is still another possibility to think of. One may imagine test bodies which absorb entirely every radiation that strikes them, whatever be its penetrating power. Such a test body would indicate not the dose, but the intensity  $I$ , or the surface energy  $F$ . It is possible that the "intensimeter" of Fürstenau realises this condition; but decisive evidence is still wanted. The author states that the instrument must be exact because it satisfies the law of the inverse square of the distance, but this is true of other instruments, and is no proof of accuracy of measurement. Every carefully gauged scale satisfies the law of the inverse square; it is the first condition for any radiometric apparatus. This alone does not suffice to show that a measurement is independent of the penetrating power. The Sabouraud disc, with the Holz knecht scale, the Kienböck quantimeter, etc., all satisfy also the law of the inverse square, yet their results are very discordant if they are compared for rays of different penetrating power. We see, then, that there is still an abundance of questions and problems to be solved before we can arrive at any system of measure answering all our needs. So much the more must there be no delay in attacking the great task of supplying the urgent needs of the radiologist.

Since science is international, a number of scientists have agreed to start an International Committee of Radiometry, to study these problems and finally to establish international units of radiometry. There is to be an International Institute of Radiometry, which will have a double task: to furnish to the committee all experimental work necessary for establishing the international units, and to gauge and control all radiometric instruments sent to it. This will do away with that troublesome multitude of units and scales which are an ever-increasing nuisance to our science. This institute will fulfil for radiometry the same useful task which the International Institute at Sèvres has done, and still does, for lengths and weights.

The committee of organisation has already been chosen, and its first report will soon be submitted to the scientific societies of all countries, whose co-operation will be indispensable.

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