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The Physical Basis of Light Therapy.[1]

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The Spectrum of Radiation.

The visible spectrum is only a small portion of the complete spectrum of ethereal waves. Beyond the violet with progressively decreasing wave-lengths, come successively the radiations called 'ultra-violet,' soft X-rays, hard X-rays, the gamma rays of radium, and the very penetrating radiation, the so-called cosmic rays, which have only recently been proved to be of extra-terrestrial origin. Similarly, beyond the red, in progressively increasing wave-lengths, come in turn infra-red and the Hertzian waves used in radio communication.

Table I. gives the approximate wave-lengths of the various radiations, but it must be noted that the divisions are quite arbitrary and that the various regions may overlap ; differences in properties arise solely from differences in wave-length.

Table I.

Type of Radiation.	Approximate Range of Wave-lengths.
Hertzian waves	40 kilometres to a few centimetres.
Infra-red	A few millimetres to 7000 A.
Visible spectrum	7000 to 4000 A.
Near ultra-violet	4000 to 3000 A.
Middle ultra-violet	3000 to 2000 A.
Far ultra-violet	2000 to 1000 A.
Soft X-rays	100 to 1 A.
Medium and hard X-rays (used in diagnosis and therapy)	0·2 to 0·05 A.
Gamma rays from radium C.	0·02 to 0·001 A.
Cosmic rays	0·0005 to 0·0003 A.

Note.

1 A. = 1 Angström unit = one hundred-millionth of 1 cm. $= 10^{-8}$ cm.

$1\mu = \frac{1}{1000}$ millimetre

$1\mu\mu = \frac{\mu}{1000} = 10$ A.

Light used in Therapy.

Both natural and artificial sources of light are used for therapeutic purposes, and considerable differences of opinion exist as to their relative merits. These differences arise very largely from the fact that the relative distribution of energy amongst the infra-red, visible, and ultra-violet portions of the spectra of the different sources varies over wide limits.

Numerous observers have noted the close parallelism between pigmentation due to exposure to light and beneficial therapeutic results. Experiment has shown that the solar radiations which are most active in producing pigmentation of the skin and hæmobactericidal effects are those between 2900 and 3000 A., or, in other words, those which are situated in the middle ultra-violet part of the spectrum. Infra-red and visible radiations may certainly influence the rate at which these effects are produced, but in general cannot themselves produce them.

On account of the spectral region used and the effects produced, light therapy is often called 'ultra-violet light treatment,' 'phototherapy,' or 'actinotherapy.' More often these terms are used in connexion with artificial sources of light to distinguish such treatment from 'heliotherapy,' or sunlight treatment.

Sunlight.

The natural source of ultra-violet radiation is the sun. The spectrum of sunlight after filtration by the earth's atmosphere extends continuously from the infra-red to the middle ultra-violet regions (30,000 to 2900 A.), but its limits are influenced by the seasons, height of the sun above the horizon, altitude of the place of observation, water vapour content of atmosphere and atmospheric pollution. The lower the sun is in the heavens, the greater is the length of path through the earth's atmosphere that its radiations have to traverse, and the resulting absorption considerably shortens the range of the spectrum. The intensity of its ultra-violet radiation reaches its maximum about one hour after midday on a clear day. Dull, cloudy weather, coupled with atmospheric pollution due to smoke and chemical fumes, may practically reduce to zero the intensity of these active rays in the neighbourhood of a large city.

It is important to note that the total ultra-

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violet radiation from the sky is more than that from the direct sun. Even with the sun at its zenith the ultra-violet radiation from it does not exceed 90 per cent. of that from the blue sky, whilst with a low sun the sky yields far more. This addition to the amount of ultra-violet radiation which a patient receives from the direct sun is due to the scattering of the sunlight by the smallest particles of the atmosphere. The effect is the more pronounced the shorter the wave-lengths involved. As Rayleigh has shown, the amount of energy scattered by a particle of given size varies inversely as the fourth power of the wave-length, and consequently the phenomenon exhibits itself more in the ultra-violet than in the visible spectrum. Thus — a fact of great practical importance—it is not essential to be exposed to the direct sun in order to receive the benefits of heliotherapy.

The above considerations show us that treatment by natural sunlight (heliotherapy) is intimately associated with geographical and climatic conditions. In the Alps, at altitudes of above 5000 ft., pure, fresh, dry air and an almost constant daily supply of sunlight are easily obtainable, whereas in England the sun appears only erratically, and its ultra-violet component varies rapidly within wide limits, rendering dosage difficult and regular treatments impossible. For these reasons, artificial sources of radiation have been developed by which constancy of output can be strictly controlled.

ARTIFICIAL SOURCES OF ULTRA-VIOLET RADIATION.

All the artificial sources of light used for therapeutic purposes are heterochromatic (that is, emit a broad band of wave-lengths), since, up to the present, no one has designed a practicable source of monochromatic radiation of sufficient intensity to be of definite therapeutic value.

The chief sources of ultra-violet radiation are electric arcs. Incandescent electric lamps with their bulbs made of fused quartz or of glass manufactured for its special transparency in this region of the spectrum (such as vita-glass) are occasionally used for some purposes, but their low energy output makes their general use impracticable.

The arc-lamps usually employed are of two types, namely, (*a*) open arcs, and (*b*) enclosed arcs.

(*a*) Open arcs have electrodes of iron, tungsten, metallic alloys, or carbon. Carbon electrodes may be either solid, 'neutral cored,' or 'impregnated.' Neutral cored carbon electrodes have a soft core of carbon powder mixed with a small amount of some substance such as potassium silicate to ensure quiet, steady burning. Impregnated carbon electrodes have mixed with the carbon powder, either salts of various metals, powdered metals, or a central wire core. Thus 'white flame' carbon electrodes usually contain the fluorides of the rare earths obtained as residues from monazite sand; 'blue flame' carbons contain iron. The ultra-violet radiation emitted by these arcs varies greatly with the chemical composition of the electrodes and the current between them. A high current density is necessary for high efficiency.

(*b*) Enclosed arcs are mercury vapour lamps with fused quartz (not glass) envelopes.

All these lamps produce ultra-violet radiation of sufficient intensity and satisfactory quality for therapy. Each differs from the rest in spectral range and has its special advantages and defects.

One of the varieties of carbon arc is usually employed in institutions when group treatment is given, and a mercury vapour lamp for individual or localised treatment. The order of the maximum relative percentage of ultra-violet radiation of wave-lengths less than 3200 A. in the total radiation emitted by the above sources, is

Mercury arc.
Impregnated carbon arc.
The sun.
Neutral cored carbon arc.
Incandescent electric lamp.

The radiation from the neutral cored, or solid electrode carbon arc is similar to that of the sun, in that it is relatively weak in radiation of wave-lengths less than 2900 A. It is, however, strong in infra-red radiation of wave-lengths longer than 30,000 A., which the earth's atmosphere has eliminated from the solar rays.

Special dispositions are required to maintain metallic arcs on an alternating current supply.

We know that radiations from the middle ultra-violet region can exert marked bactericidal properties *in vitro*, and also 'activate' certain substances such as ergosterol, etc., in such a manner that when ingested they tend to cure rickets. We also know that the bactericidal power of the blood is enhanced, and the mineral metabolism promoted, when the living animal is subjected to these rays. Some effects, such as the erythema following irradiation, only appear after an interval of time—called the 'latent period'—has elapsed since the exposure terminated. How these effects are produced is not known with certainty, and light therapy is still mainly empirical.

PHOTO-ELECTRICITY.

For every substance there are radiations which will cause some of its atoms to eject electrons and consequently leave the stripped atoms positively charged. This phenomenon is called ionisation or photo-electric emission. For it to occur, it is only necessary that the wave-length of the incident radiation should be less than a critical or threshold value, which is characteristic of the atom ionised. For most substances the critical wave-length lies in the ultra-violet spectral region, but for some it occurs in the visible spectrum, and for cæsium is actually in the infra-red region (see Table II.). The wave-length which will cause maximum emission of electrons from any element is approximately two-thirds of the critical wave-length for that element, and for sodium, potassium, and cæsium lies in the visible spectrum. The velocity of emission of photo-electrons depends on the wave-length of the exciting light, whilst the number emitted depends upon the intensity of the light.

TABLE II.

Element.	Critical Wave-length in A. for Photo-electric Effect.
Graphite	2615
Copper	2665
Selenium	2670
Iron	2870
Cadmium	3130
Zinc	3425
Sodium	6000 (about)
Potassium	7000 ,,
Cæsium	8000 ,,

As the emission of photo-electrons from an illuminated surface is very susceptible to the presence of condensed surface films of gas or vapour, it is necessary for reproduction of photo-electric effects that the surfaces be prepared, and maintained, in high vacua.

FLUORESCENCE AND PHOSPHORESCENCE.

Certain substances, when stimulated by radiation of one wave-length, emit radiation of a different wave-length. If the emission only appears whilst the stimulus is being applied the phenomenon is called fluorescence, but if it persists after the stimulus has ceased it is called phosphorescence.

Phosphorescence is only exhibited by solids: fluorescence by solids, liquids, and gases. Although Stokes stated that fluorescent light was always of longer wave-length than the exciting light, we now know that this rule, though generally valid, is not invariable.

Fluorescence is caused by the return to a more stable position in an atom, of electrons displaced by the exciting radiation.

PHOTO-CHEMICAL ACTION.

That chemical action can be brought about by light has been known for a very long time, and is familiar to everyone through photography. Photo-chemical actions are usually divided into three classes, namely:

(*a*) Photo-catalytic actions in which light only accelerates an irreversible process. Here the light cannot be regarded as stored up in the transformed substance as chemical energy. The action only occurs in the presence of a catalyst. Thus, in the presence of colloidal uranium, formaldehyde may be synthesised from carbon dioxide and water, by exposure to sunlight. Without the uranium no formaldehyde is formed.

(*b*) True photo-chemical equilibria in which the equilibrium of some reversible reactions is altered by light, and again brought back to the initial state on standing in the dark. (Compare the behaviour of a selenium cell which conducts electricity better when illuminated than in the dark.)

(*c*) False chemical equilibria, which are irreversible processes composed of two or more photo-catalytic reactions.

In certain cases the initial action of radiation is to decompose some substance (called a 'negative catalyst') which hinders the chemical action which takes place some time after the irradiation of the system has proceeded (cf. erythema and pigmentation).

Photo-chemical actions are subject to the following two laws:

Grotthus's Law.—Radiation must be absorbed in order to bring about the reactions which it produces.

Bunsen-Roscoe Law.—The amount of substance decomposed by radiant energy is proportional to the amount of radiant energy absorbed—that is, is proportional to the product of the intensity of the radiation, by the time for which it is applied.

In connexion with the above, it should be noted that radiations of different wave-lengths may produce different actions on one and the same substance. It appears to be a fairly general rule that of two radiations which produce opposite effects, it is the longer wave-length which produces the oxidising action and the shorter wave-length the reducing action. The decoloration, by infra-red rays, of glass which has been coloured by ultra-violet rays, illustrates this.

Several writers have claimed that they have detected a similar opposing action, or physiological interference, of infra-red and ultra-violet radiations in the production of erythema of the skin, or the immobilising action on bacteria *in vitro*. These observations, which have not yet been confirmed beyond doubt, are of great interest from the point of view of choice of an artificial source of radiation and the measurement of dose.

Unlike most chemical reactions, in which rise of temperature produces a marked increase in the velocity of reaction, the effect of temperature on photo-chemical reactions is usually very small.

ABSORPTION, TRANSMISSION, AND REFLECTION.

Certain substances strongly absorb light corresponding to some parts of the spectrum, and transmit the remaining light unchanged. This phenomenon is called selective absorption. It produces dark bands, called absorption bands, in the spectrum of the transmitted light.

Absorption bands are characteristic of the absorbing substances and serve to identify them by examination with a spectroscope, for example, the bands of hæmoglobin and chlorophyll.

By making use of the selective absorption bands of different substances, it is possible to make light filters which will transmit narrow bands of wave-lengths in chosen parts of the spectrum.

The reflecting, transmitting, and absorbing powers of a substance for light in the visible spectrum give no trustworthy indication of these properties for radiations in the infra-red or ultra-violet regions.

The percentage penetration of *dead* human skin by ultra-violet radiation is given in Table III., which records some measurements by Hasselbalch.

TABLE III.

Thickness of dead skin in mm.	Wave-length in A.						
	4360.	4050.	3660.	3130.	3020.	2970.	2890.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
0·1	59	55	49	30	8	2	0·01
0·5	7·0	5·0	3·0	0·3	—	—	—
1·0	0·5	0·3	0·08	0·006	—	—	—

The practically negligible penetrative power of the biologically active ultra-violet rays indicated by this table is very marked. Definite clinical evidence is available, however, which shows that ultra-violet radiation of wave-lengths shorter than 2900 A. can produce marked physiological effects. The difficulty of explaining these effects by any direct or indirect action has recently been considerably lessened by the work of Macht and his co-workers. These investigators have shown that the penetration of ultra-violet radiation into *living* tissue is greater than for dead tissue. This is brought out by comparing the figures in Table III. with those published by Macht and summarised in Table IV.

TABLE IV.

(Transmission of monochromatic ultra-violet radiation through living animal tissue, 1·175 mm. thick.)

Wave-length in A.	4050	3660	3130	3025	2800	2650	2537
Transmission (per cent.)	16·3	11·4	19·5	27·2	56·3	23·8	42·8

Infra-red and luminous rays can penetrate more deeply than ultra-violet rays. Sonne has shown that the luminous rays can produce a greater elevation of temperature below the skin than the infra-red rays, and asserts that this heating effect due to absorbed luminous rays assists in the destruction of toxins and formation of antibodies.

Ordinary window glass transmits a portion of the ultra-violet nearest the visible region of the spectrum, but cuts out completely all wave-lengths less than 3100 A. It thus absorbs all the solar radiation which produces pigmentation, etc. Fused quartz and water transmit ultra-violet radiation quite freely down to wave-lengths of about 2000 A. Corning glass 980 A. transmits all solar radiation almost as freely as the more expensive fused quartz. Vita-glass resembles Corning glass 980 A. in its properties, but is not so transparent for equal thicknesses, and also exhibits some deterioration in transmission after exposure to sunlight.

'Wood's' glass, which cuts out most of the visible spectrum, transmits a band of wave-lengths in the near ultra-violet region about 3600 A. and is therefore useful for fluorescence experiments.

Snow is a good reflector of ultra-violet radiation, and snow-blindness is due to the reflection by it of the short waves of sunlight.

Polished surfaces of magnalium, nickel, and aluminium make the best reflectors of the middle ultra-violet region of the spectrum for ordinary purposes; silvered mirrors are much poorer.

The biological effect produced by uninterrupted exposure to ultra-violet radiation appears to be directly connected with, and in proportion to, the energy absorbed (Bunsen-Roscoe Law). The intensity of the incident radiation and the time of exposure are the external quantities, and the absorption coefficient of the skin the internal quantity, which determine the quantity of energy absorbed, and therefore the biological effect.

It has already been pointed out that all sources of radiation used in light therapy are heterochromatic, and that radiation from them is absorbed differentially by the skin. Reference has also been made to

Sonne's assertion concerning the effects of luminous rays, and also to the possibility of antagonistic action between infra-red and ultra-violet rays. Throughout this article it has been assumed that exposure to *ultra-violet* radiation is essential for the production of the recognised benefits of light treatment. This assumption seems to be perfectly in agreement with experience. What is not yet satisfactorily settled is whether (and if so, what) other wave-lengths are also useful or harmful.

It is this lack of knowledge which renders the physical measurement of the therapeutic efficiency of an arc-lamp uncertain.

DETERMINATION OF QUALITY.

The quality of the radiation emitted by a given source may be determined by passing the radiation through a spectroscope and examining the emergent beam. As glass absorbs both infra-red and the middle and far ultra-violet rays, it cannot be used for this work, and therefore the prisms and lenses used are of quartz or rock-salt.

For the visible and ultra-violet regions down to wave-lengths less than 2000 A., this examination may be done by direct observation, the rays in the ultra-violet being detected by the visible fluorescence caused either in uranium glass or in a smear of vaseline. Alternatively, these regions may be recorded on a photographic plate. For the infra-red spectrum we must use one of the methods mentioned later. When examined by any of the above methods, it will be found that whereas the spectra of tungsten and mercury consist mainly of bright lines, that of pure carbon is practically a continuous one, being similar in character to the solar spectrum. From the known constants of the apparatus, or by making use of reference lines of known wave-lengths, it is possible to determine the range of wave-lengths in a spectrum and the wave-lengths of any bright lines in it.

DETERMINATION OF INTENSITY.

In determining the intensity of radiation proceeding from a source and falling on a surface, we have to decide which of the following three quantities we wish to measure :

1. The total intensity.
2. The intensity of a group of radiations of differing wave-lengths.
3. The intensity of the radiation of a single wave-length.

In measuring the total intensity, no preliminary analysis of the radiation is required. To measure the intensity of a group of radiations, either colour filters must be used to isolate it, or some instrument employed which is only sensitive to radiations in the given region.

For the measurement of the intensity of the radiation of a single wave-length, the total radiation is first resolved by means of a spectroscope and the particular radiation caused to pass through a narrow slit to the measuring instrument.

Whichever of the three intensity measurements is to be made, the following methods are available: (*a*) Thermal, (*b*) fluorescent, (*c*) chemical, (*d*) electrical.

THERMAL METHODS.

Either a thermopile or bolometer may be used.

The thermopile consists of a number of thermocouples or pairs of electrical conductors of different metals, and is used joined in series with a galvanometer. Whenever one junction of a thermocouple has its temperature raised above that of the other, an electric current will flow through the galvanometer. By allowing the radiation to fall on the junctions of a thermopile which have been covered with lamp-black and by using a sensitive galvanometer, measurements may be made over the complete range of wave-lengths used in light therapy.

The bolometer consists essentially of a blackened fine metallic wire the rise in temperature of which, when radiation falls upon it, alters its electrical resistance. This change in resistance, when measured by suitable means, gives the intensity of the absorbed radiation. The sensitiveness of both thermocouples and bolometers is increased by mounting them in evacuated vessels to reduce the cooling effect of the surrounding gas.

FLUORESCENT METHODS.

In practice these methods are only applicable to measurements made in the ultra-violet region. They depend upon the fact that the intensity of the fluorescent light emitted by such substances as barium-platino-cyanide and zinc sulphide is directly proportional to the intensity of the exciting radiation.

CHEMICAL METHODS.

A great variety of photo-chemical reactions have been proposed and used for measuring either total or ultra-violet radiation. The effect most frequently used is the reduction of silver chloride as in photography. Here, instead of weighing the silver liberated, the resulting blackening is used as a measure of intensity, either by finding the time necessary to produce a standard blackening, or the blackening produced in a definite time.

Leonard Hill has devised a system of measurement of the ultra-violet radiation of wave-lengths shorter than about 3600 A. by making use of their bleaching effect on a solution of methylene blue in acetone.

The standard solution is exposed in a quartz tube and the 'exposure' measured by comparing its tint with some standard tints calibrated in terms of the lethal effect on infusoria. The scale adopted is quite an arbitrary one.

Janet Clark has suggested using the blackening effect of ultra-violet radiation on lithopone (a pigment containing zinc oxide, zinc sulphide, and barium sulphate) for intensity measurements. This substance, when moistened with water, darkens under the influence of rays of wave-lengths less than 3200 A. It thus appears to afford a simple colorimetric method of measuring those rays which can produce an erythema of the skin.

ELECTRICAL METHODS.

These generally make use either of the photoelectric property of some metal—generally zinc or cadmium—or the fall in electrical resistance of selenium when illuminated. A glance at Table II. will show what metal is best suited to the particular radiation to be measured. In principle, a photoelectric cell consists of an insulated plate of metal connected to an electrometer or gold-leaf electroscope, the system being negatively charged. Under the influence of a suitable radiation, the plate loses its charge at a rate dependent upon the intensity of the radiation.

The action of a 'selenium cell' is somewhat different. As ordinarily used, the change of resistance of the cell when illuminated is measured by the change in current through a microammeter connected in series with the cell and an energising battery. This effect can be produced by infra-red, visible, ultra-violet, Röntgen, and gamma radiations, and is not the normal photo-electric effect.

It is easily seen that any of the instruments described above can readily be used to give a trustworthy check on the emission of a given source at different times. Their value in comparing the different emissions of different sources is not quite so certain.

INVERSE SQUARE LAW.

The intensity of the radiation falling on a surface can only be assumed to diminish according to the law of inverse squares (1) when the active dimensions of the source are small compared with its distance from the surface, and in addition (2) when no reflector is used.

DANGERS AND PRECAUTIONS.

Three common sources of danger in connexion with the use of artificial sources of ultra-violet radiation, and the precautions necessary to avoid them, are:

(1) The production of a severe conjunctivitis, through looking directly at an arc. Operators and patients should always wear protective goggles or shades.

(2) Over-exposure through continuing a course of treatment after replacing an old mercury vapour arc-lamp by a new one, or substituting different electrodes in an open arc. An intensity measurement should always be made when using a new source.

(3) Electric shock through touching 'live' electrical conductors. Several fatalities have occurred through the use of electrical apparatus in bath-rooms, where the conditions for short circuiting the supply through the body are almost ideal.

No installation should be set up in such a position that a patient can touch a 'live' electrode and a water-pipe or 'earthed' conductor at the same time. It is advisable to use a floor covering of linoleum or carpet.

CONTRA-INDICATIONS TO LIGHT THERAPY.

In addition to the purely physical dangers mentioned in the last paragraph, there are many physiological and pathological conditions—such as menstruation in women, low blood pressure, fever, hyper-photo-sensitiveness, etc.—which are contra-indications to the therapeutic use of ultraviolet radiation. The discussion of these lies outside the scope of the present article.

Biological Action of Ultra-Violet Rays.

By Prof. LEONARD HILL, M.B., F.R.S.

RADIATIONS from sources of energy—sun, stars, etc.—are conducted by waves in a hypothetical ether with a velocity of 186,000 miles per second in the case of light. Ether radiations include the Hertzian waves used in radio with wave-lengths extending to a thousand metres or more, then the infra-red, with wave-lengths from 60,000 to 700 $\mu\mu$, then the visible with wave-lengths from 700 $\mu\mu$ (red) to 400 $\mu\mu$ (violet). Beyond the visible lie the invisible ultra-violet rays with wave-lengths from 400 $\mu\mu$ to 100 $\mu\mu$, and beyond these come the soft X-rays and