PHYSICAL NATURE OF RADIATIONS USED IN INDUSTRY *

BY

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The principal radiations may be divided into two types, corpuscular and electro-magnetic radiations. Corpuscular radiations are those having the properties of particles, as, for example, alpha rays, beta rays and neutrons, while electro-magnetic radiations are those with wave-like properties. Examples of electro-magnetic radiations are gamma rays, x-rays, ultra-violet and actinic rays, visible radiation, infra-red rays and radio waves. Though this division is justified by experiment it should be pointed out that recent experiments have demonstrated that particles show wave-like properties and waves particle-like properties.

Corpuscular Radiations

These radiations are emitted in the natural or artificial disintegration of atomic nuclei.

Alpha particles are the nuclei of the gas helium; they carry positive charges and have four times the mass of the hydrogen atom. They are copiously and continuously emitted by naturally radio-active substances like radium and occur with well-defined energies, usually about 5 million electron volts. On the average they travel with one-twentieth of the speed of light. In spite of their high energies and great speeds alpha particles have little penetration because they dissipate energy rapidly by the formation of ions. An alpha particle with a range of 4 cm. in air at atmospheric pressure (equivalent to a thin sheet of paper), produces as many as 275,000 ions along its track. The tracks left by alpha particles can be made visible by the Wilson cloud chamber. A photograph of alpha particles tracks is reproduced in fig. 1. The intense ionization and the straightness of the tracks may be noted.

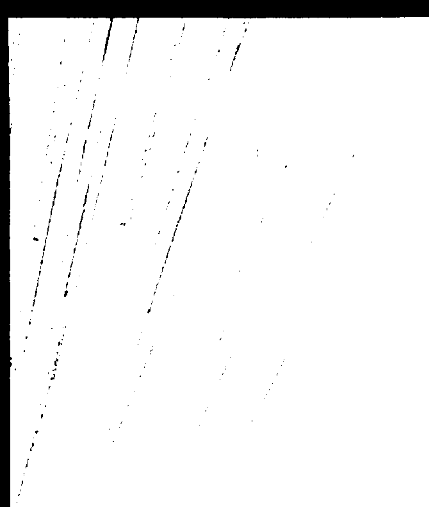

FIG. 1.—Tracks left by alpha particles in the Wilson cloud chamber. (After Blackett and Lees.)

Beta particles are high speed electrons ejected from radio-active nuclei or from the outer shells of electrons by gamma rays. Their energies range up to 10 million electron volts and they have velocities approaching the velocity of light. The ranges of beta particles are much greater than alpha particles because the ionization loss along their paths is much less. The small ionization loss is shown by the thinness of the track left in the Wilson cloud chamber. A high-speed beta particle has a range of about 1000 cm. in air or 1 cm. in water. Beta particles are highly scattered. If a beam of beta particles falls normally on a thin sheet of metal of high atomic number, 50 per cent. of the beam is scattered through more than 90 degrees.

Neutrons are not yet used in industry. They are neutral particles of mass equal to the hydrogen atom and are emitted in large numbers when certain elements, e.g. beryllium, are bombarded with the alpha particles from radium. They may be produced artificially by the Lawrence cyclotron. Their ranges are very great because their ionization loss in matter is extremely small. They are very difficult to absorb. The best absorbers known are water and paraffin.

Electro-magnetic Radiations

Electro-magnetic radiations have wave-like properties, that is they show the phenomena of reflection, refraction, dispersion, interference and diffraction. The only difference between the different types of radiation is a progressive change in wave-length from the shortest electro-magnetic radiation known, gamma radiation, to the longest, radio waves. They all travel with the velocity of light.

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Many of the properties of these waves can be illustrated by water waves. Thus if two sets of water waves of the same wavelength cross, interference effects are observed in the region of crossing. At some places in this region much higher waves are observed while at other places there is still water because the 'humps' of one set of waves overlap the 'hollows' of the other set. Exactly the same effect is observed in the case of light and x-rays (see fig. 2) and, in fact, for all electro-magnetic radiations.

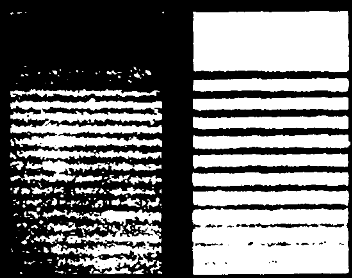

FIG. 2.—Interference fringes taken with (*a*) x-rays of wavelength 8·33 A.U. (after Kellstrom), and (*b*) visible light of wavelength 4358 A.U. (after White).

The dark lines in the figure correspond to regions of destructive interference, i.e. no light, and the bright lines to regions of constructive interference. By this and many other experiments it has been proved that all the radiations classified as electro-magnetic have similar properties.

Gamma rays are electro-magnetic radiations of wavelengths from 0·005 to 1·3 A.U. emitted by radio-active nuclei. Their penetration is very great, the intensity being reduced only 50 per cent. by 2 inches of iron. Energy is lost by the production of beta particles (photo-electrons ejected from the outer shells of atoms), scattering and, for very short waves, the creation of pairs of electrons.

X-rays are electro-magnetic radiations of wavelengths from 0·01 to 10 A.U. A thickness of 3·5 cm. lead is needed to protect the body from 600 Kv. x-rays. Wilson cloud chamber photographs show that x-rays lose energy by the production of photo-electrons (see fig. 3), and by

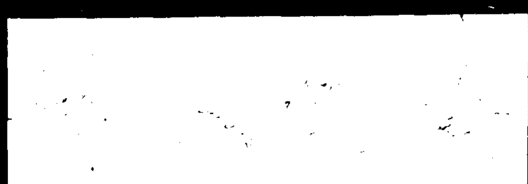

FIG. 3.—Tracks left by electrons in the Wilson cloud chamber: tracks are from low energy photo-electrons (produced by a beam of x-rays) which are identical with slow beta particles. (After Nuttall.)

scattering. The medical effects are due to photo-electrons. The total length of track of all the photo-electrons produced in a small volume of the body by a comparatively short irradiation with x-rays may be of the order of thousands of miles.

Ultra-violet and actinic rays (wavelength range, 2500–4500 A.U.), *visible radiation* (4000–8000 A.U.), and *infra-red rays*, correspond to energies of from 5 volts and 0·1 volts. Medical effects may be physiological, photo-chemical or thermal. These radiations may be emitted or absorbed by matter in the form of line, band or continuous spectra. Line spectra are associated with electronic energy changes in atoms while band spectra are associated with electronic, vibrational and rotational energy changes in molecules. Continuous spectra may be produced by atoms or molecules in the gaseous, liquid or solid states. The continuous spectra produced by liquids and solids may be due to line or band absorption broadened to continua by the intense atomic and molecular fields. Examples of line and band emission spectra are shown in fig. 4. An

FIG. 4. Examples of line and band emission spectra. The line spectrum, marked (*a*), is part of the spectrum emitted by the iron arc: and the band spectrum, marked (*b*), is emitted by the diatomic molecule antimony fluoride (SbF). The line spectrum is superimposed on the band spectrum.

example of line absorption spectrum is the Fraunhofer spectrum of the sun which is due to the absorption by the cool gases in the outer layers of the sun of the continuous spectrum emitted by the white-hot interior. A good example of very important continuous absorption is the narrow absorption band of chlorophyll in the near infra-red. By this absorption band vegetation absorbs energy from the sun and life on the earth is made possible.

Summary

A description is given of the physical nature of the principal radiations used in medicine. The radiations are divided into two main types, corpuscular and electro-magnetic radiations. The corpuscular radiations include alpha particles, beta particles and neutrons; while the electro-magnetic radiations include gamma rays, x-rays, ultra-violet radiation, visible radiation and infra-red rays. The medical effects are for the most part due to the production of photo-electrons but they may also be physiological, photo-chemical or thermal.

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MEDICAL ASPECTS OF RADIATIONS USED IN INDUSTRY *

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Present knowledge of the potential danger of many varieties of radiation, and of the measures necessary to safeguard industrial workers against such danger, is based first upon the actual experience of early research workers in this field, and, second, upon preventive measures instituted by various medical bodies for personnel engaged in x-ray and radium therapy.

The radiations with which industry is chiefly concerned are x-rays, infra-red, light, and ultra-violet rays, radium, and to a much smaller extent, ultra-short waves.

X-rays

The story of the injuries received by pioneers in the x-ray field is a sad one, so well known that only brief reference need be made to it. It is interesting to note, however, that Röntgen himself, who discovered x-rays in 1895, escaped injury chiefly because most of his experiments were photographic only, and also because he used x-ray tubes placed in a zinc box and protected by lead screens.

Reports of soreness of the eyes, dermatitis and loss of hair began to come in about 1896, but even in 1899 it was still believed by many authorities that these were due to chemical or electrical conditions in the skin or, as in the case of Dr. Hall Edwards who eventually died of x-ray can[illegible], to the developer used. The first [illegible] x-ray cancer in a workman employed in maki[illegible] ray tubes, and developing from a lesion on the back of the hand, was described in 1902 ; but Dr. Hall Edwards' reports on his own injuries in 1904 pro[illegible] the classical description of this fatal condition. The redness of the skin, transverse lines on the brittle nails, cracks of the epithelium, warty growths, sores which would not heal, and the very severe pain, finally necessitating amputation of fingers and forearm, form a picture which was to be repeated in other unfortunate victims before the necessity for suitable preventive measures was fully recognized.

Injuries due to X-rays. Injuries to the *skin* are perhaps the best known signs of x-ray damage, perhaps because they are so obvious, especially in the acute stage. An x-ray burn may consist only of a patch of acute erythema, which gradually disappears in the course of a few weeks, but it may go on to necrosis and ulceration which is extremely difficult to heal. It is probable, however, that a single burn never initiates cancer. Chronic x-ray dermatitis is a different and entirely characteristic pathological condition, involving processes of both atrophy and regeneration. Side by side with atrophic loss of the epidermal appendages and obliteration of small blood vessels, leading to areas of necrosis beneath the epidermis, goes reparative proliferation of surrounding tissues. The clinical signs of this combination of atrophy and repair are thickening of the epidermis, hyperkeratosis, cracks, with degenerative changes in the deeper tissues—in other words, a pre-cancerous condition.

There are also the later skin reactions, appearing only some time after exposure has ceased, even as long as several years after. These may consist of telangiectases, areas of pigmentation and atrophy, localized thickenings and warts, generally on the dorsum of the hand, or later ulceration due to obliterative endarteritis and lymphangitis.

The *blood changes* caused by excessive exposure to x-rays are shown first of all by the white cells. A gradually increasing leucopenia, sometimes preceded by a transient leucocytosis, is the most constant diagnostic sign. The leucopenia is often accompanied by a lymphopenia, since the lymphocytes are specially sensitive to x-rays, or sometimes by a relative lymphocytosis. If this condition is detected at an early stage and the subject removed from exposure, it is entirely curable, but if allowed to progress it may culminate in severe and even fatal depression of the bone marrow—aplastic anaemia. Cases of leukaemia as the final stage have also been reported, but there appears to be some doubt as to the direct connection between the condition and general x-ray radiation. There seems no scientific reason, however, why leukaemia should not be the end-result of an aplastic marrow, possibly as an over-compensatory regenerative process. We do know that benzol poisoning, which characteristically causes aplasia of the bone marrow, does at times end fatally, with the bone marrow in a condition of hyperplastic leukaemia; and, in fact, benzol leukaemia, though not nearly so common as benzol anaemia, is a recognized clinical entity.

* A post-graduate lecture given at Manchester University, January 30, 1944.

With regard to the *generative organs*, sterility has been known to occur in some male radiographers when protection has been inadequate. Some of these cases have eventually recovered. In female radiographers and nurses the percentage of sterility has been found to be high, and there is said to have been a rather high percentage of developmental defects in any children born, but the evidence is not conclusive.

Industrial Uses. The use of x-rays for detecting flaws in castings and other metal articles and in diffraction processes is constantly increasing and the voltage of the apparatus varies considerably. For small castings of light alloys the range is usually from 30 to 100 kilovolts; for heavy large castings, such as bomb-carriages, from 100 to 200 kv. and in some cases up to 400 kv. In America much more powerful installations—up to 1000 kv.—are used, but have not yet been introduced into this country.

The chief danger to x-ray operatives arises when the work is chiefly screening, rather than photography. Protection from the direct beam can, of course, be afforded by lead screening of the tube. The danger of *scatter radiation* is less obvious and therefore often less carefully guarded against, and it has not been unusual, until fairly recently, to find x-ray rooms littered with numerous articles awaiting examination, all acting as contributory sources of scatter radiation.

Preventive Measures. The measures at present recommended to all users of industrial x-rays are based on the original recommendations of the British X-ray and Radium Protection Committee, which was formed in 1921 with the object of preventing casualties to x-ray and radium workers. These formed the basis of the International Recommendations adopted at Stockholm in 1928 by the Second International Congress of Radiology. They included general hygienic conditions for x-ray rooms —size, ventilation, temperature and layout of the apparatus; protection of the x-ray tube by a sufficient thickness of lead or its equivalent; the use of mirrors; provision of screens for fluorescent work; protection against scatter radiation by placing the operator outside the x-ray room behind walls containing the necessary lead or its equivalent; protective clothing; a working week of not more than 35 hours with four weeks' holiday a year; and periodical blood examinations. These recommendations are designed to limit the exposure received by the operator to what is considered the tolerance dose of one R per week, and to detect the earliest signs of injury.

Application to Industrial X-ray Exposure.—These preventive measures apply with equal force to the protection of industrial x-ray operatives, though they are not at present statutory. Naturally, a continuous check is kept by the Factory Department on the conditions obtaining in the x-ray industrial field. It has to be remembered that, even with a well installed and well protected x-ray apparatus, the human factor comes into play more markedly with the industrial worker, who is less likely to be aware of the danger and more likely to take liberties with it, than with the trained medical radiographer. X-ray burns, for instance, should not occur with a fully protected installation and lead rubber gloves, but even where these conditions have been fulfilled and where advice and instructions have been given, they have occurred, because the worker has been unable to realize that putting his uncovered hands in the track of an invisible ray even for a short time could do any harm.

It will be appreciated that the work in factories differs from that in hospitals; longer hours and more continuous spells may have to be worked, and the risk of scatter radiation may be greater. The Chief Inspector of Factories decided therefore, in 1942, after consultation with representatives of various interested bodies, to have a preliminary survey made of the actual conditions of exposure in factories using x-rays. A circular letter was sent to managements inviting them to co-operate in a scheme by which the National Physical Laboratory undertook to measure the dosage revealed by dental films worn for one week by the operatives. If these showed evidence of a dosage greater than the tolerance dose of one R per week, the National Physical Laboratory would investigate the plant, and the operative in question would be asked to undergo a blood examination. In this way it is hoped to link up actual exposure with the condition of health of the workers. The results so far have been very encouraging with regard to the dosage which industrial x-ray workers on the whole are receiving. In nearly all the large number already investigated the dosage varied from 0·1 to 0·3 R per week—well below the tolerance dose.

Infra-red Rays and Light

Certain industrial occupations, such as welding or brass foundry work, involve exposure to all three varieties of radiation—infra-red, light, and ultra-violet; in glass manufacture it has been shown that infra-red is the chief harmful component; and in electro-welding the light and ultra-violet rays form the greater hazard. Exposure to excessive light, as in gazing at bright objects, may cause transient scotomata which disappear on rest and can be prevented by wearing suitable glasses such as those prescribed by the British Standard Specification Pamphlet No. 679. Infra-red radiations physiologically produce vasodilatation of the skin vessels, and stimulation of cell activity, thus promoting healing and tissue repair. They do not penetrate very far before being converted into heat, but some do penetrate the dermis and may cause an actual rise of body temperature. In excessive dosage they produce severe metabolic disturbance, skin burns and lesions of the eye.

Industrial Exposure and Injury. The chief processes in which excessive exposure to infra-red radiation is likely to occur are foundry work, welding, glass manufacture, and some varieties of furnace work. Heat cramps are, of course, a

Amendment Order that all luminizers employed more than a year shall have three months of complete removal from exposure will no doubt prevent this trend towards a depressive effect from degenerating into a true leucopenia. Consultation with many haematologists as to the significance, if any, of the initial lymphocytosis and the presence of abnormal cells, appears to confirm the author's opinion, which is that it represents an initial stimulative effect of small doses of radio-active material. In itself the phenomenon is not necessarily harmful, but it must be remembered that hyper-stimulation over a long period might eventually produce depression.

Radon Estimations.—An attempt is being made here, as has already been done by Robley Evans in America to keep a further check on the health of luminizers by estimation of radon in their exhaled air, in order to ascertain whether in fact any radium is deposited in the tissues. Research is being carried out on these lines, under the direction of the M.R.C. by Professor Russ of the Middlesex Hospital, and it is hoped to make further use of the results, but there are great difficulties of technique and of arriving at definite conclusions. The method will, it is hoped, be a valuable adjunct to the prevention of serious effects.

A *dental film test*, similar to that for x-ray workers, is also being worked out by the National Physical Laboratory.

It will be seen, therefore, that while at present there is no reason to fear for the health of luminizers, it is very necessary in view of the cumulative effect of radium, and again taking into account the human factor which sometimes defeats the strictest regulations, not to relax a single precaution and to keep a constant watch on any developments that might arise. So far as the Factory Department is concerned, this is being done.

Short Waves

A brief reference must be made to 'short waves.' As in the case of x-rays and radium, most of our knowledge of the biological effects of this variety of radiation comes from the clinical field, where short-wave therapy has been in use for some time in the treatment of inflammatory conditions, rhinitis, asthma, sepsis and the results of trauma. In industry, short waves are not at present widely used. Before the war there was a gradually increasing manufacture of television receivers and of medical short-wave apparatus, and both these sources of short-wave radiation will no doubt increase during the post-war years. It is necessary, therefore, to have some idea what danger, if any, is to be apprehended if their use becomes more extensive.

So far the only symptoms complained of have been discomfort from sensations of heat, headache and drowsiness. It appears more than probable that these are entirely a heating effect, since in actual short-wave therapy, as in diathermy, heating of the tissues is a known and desired effect.

It has often been stated that the favourable effect of short-wave therapy is due chiefly to dilatation of capillaries, but recent observations, by means of special microscopic technique, of human capillaries while short-wave therapy was being carried out, showed that there was no marked alteration in the calibre of the capillaries; there was, however, a marked increase in the rate of blood flow, which probably accounted for the rapid subsidence of oedema and resolution of septic processes. It has been suggested that the chief danger to persons exposed to short waves might arise from their selective absorption by the body owing to the great variation in resistance of the various organs and tissues, and that over-heating of the blood might be associated first with the possibility of thrombosis, and second with damage to projecting parts of the body because of the reversal of the normal cooling process that is to say, these parts would receive heat from the blood instead of having it taken away.

In actual practice, so far as all inquiries have shown, no such dangers have arisen, and the discomfort from overheating can be minimized by suitable precautions. These include: (1) Keeping out of the field as much as possible. Distant control of the apparatus is the obvious solution. (2) Using the apparatus in atmospheric conditions which best provide regulation of the body heat. This could, of course, be achieved by artificial movement of the air. (3) Suitable screening. At the same time it must be emphasized that beyond the physiological effects described little is known of any other biological or possibly cumulative properties of these rays, and if their use ever becomes an industrial problem of any magnitude a promising field of research and of vigilance will be open to the industrial medical officer.

Summary

X-rays. Used for detecting flaws in metal. Screening more dangerous than photography; 'scatter' radiation requires special precautions. Injuries—skin lesions (burns, dermatitis, pigmentation, warts, malignancy); blood changes (leucopenia, aplastic anaemia, even final leukaemia); sterility is rare. Prevention by limitation of exposure.

Infra-Red Rays. Injuries—heat cramps, skin erythema, cataract—in foundry and furnace work, welding, glass manufacture.

Ultra-Violet Rays. Injuries—conjunctivitis, corneal ulcer, iritis—in electro-welding. Prevention by spectacles or protective glass screens.

Radium. Used in luminizing. Injuries—due to alpha or beta particles, gamma-rays, or radon—causing true radium poisoning (jaw necrosis, bone malignancy, aplastic anaemia); respiratory lesions (including cancer); aplastic anaemia; dermatitis. Prevention by legislation: Mayneord's protective container; periodic blood examinations; radon estimations of exhaled air; dental film test.

Short Waves. Exposure in manufacture of television and therapeutic apparatus. Serious risk to health improbable.