With the Author's kind regards

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Royal Institution of Great Britain.

WEEKLY EVENING MEETING,

Friday, April 25, 1902.

Sir James Crichton-Browne, M.D. LL.D. F.R.S., Treasurer and Vice-President, in the Chair.

James Mackenzie Davidson, Esq. M.B. C.M. *M.R.I.*

X-Rays and Localisation.

At the end of the year 1895 Professor Röntgen announced that he had discovered a new kind of rays coming from a Crookes' Tube, which he called the X-rays. This discovery created a widespread interest in all parts of the world and among all classes of people, and the reason is not far to seek, because the fact that these rays have the power of passing through our bodies and casting shadows of our bones upon a photographic plate or a fluorescent screen, at once gave the discovery an intensely human interest.

It is my privilege to-night to tell you something about these rays and their application in surgical practice. At the risk of being too elementary, I nevertheless purpose beginning with a short historical sketch of the scientific discoveries and developments which led up to their discovery.

We will begin with the electric spark. Two types of instruments are employed to produce disruptive electric discharges; the Wimshurst or Holtz Influence Machine which, by merely turning a handle produces electricity at a high pressure. The other instrument is an induction coil, and it is the latter which I will use to-night in carrying out my experiments.

The Induction coil consists of a coil of insulated thick wire bound round a bundle of soft iron wires, such as I show you here. This is called the primary. It is introduced into the interior of a large coil, consisting of a great length of very fine insulated copper wire; this is called the secondary. In this instrument here to-night there are about nine miles of fine copper wire. The action of this instrument is based upon the discovery made in this place by that great philosopher and experimentalist, Faraday. If a current of electricity be passed through the primary coil at the moment of starting it, there is a current induced in the secondary coil in a reverse direction; and when the current is broken in the primary, there is induced a powerful reverse current in the secondary; so that at each make and break of the current in the primary we have two currents correspondingly induced in the secondary in opposite directions, but at a much higher potential.

The current induced in the secondary when the current is broken

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in the primary, is about fifty times more powerful than the current produced at the make in the primary. In this way if the terminals of the secondary are widely separated only one of the induced currents has sufficient energy to spark across, so that the secondary discharge is thus rendered unidirectional. A commutator introduced in the primary circuit enables the operator to make either end of the secondary a plus or a minus pole at will.

Induction coils are usually supplied with a spring hammer break tipped with platinum, which automatically makes and breaks the current in the primary, but to-night I shall use instead, a simple form of mercury break. This consists of a tank or small vessel containing mercury, into which one end of the primary of the coil dips. A small electric motor is placed in an inclined position, so that its spindle with a small copper blade attached at right angles to it dips down obliquely into the vessel containing the mercury. The battery has then one of its poles attached to the other end of the primary coil, while the other pole of the battery is attached by means of a spring to the spindle of the motor. It is so placed that as the motor rotates the blade at its end dips into the mercury, and in this way makes good contact and the current of the primary is made; as it rotates it comes out of the mercury and so the current in the primary is suddenly broken. To avoid arcing, the mercury is covered to a considerable depth with paraffin or alcohol. In this way we can control the number of breaks which we can produce, and if the motor is running at the same speed, the same number of makes and breaks can be repeated in the same period of time. The speed of the motor is regulated by a small adjustable resistance. The higher the voltage, the greater speed is required in the motor.

In order to increase the efficiency of the coil a condenser is always introduced as a shunt to the primary across the break terminals. A condenser consists of sheets of tin foil with sheets of paraffin paper between in such a manner that the odd numbers of the sheets of tin foil are all joined together and the even numbers are all joined together, and this arrangement allows the sheets of tin foil to be oppositely charged, and allows the break in the primary with ordinary speeds to be more sudden. Now when I start the break and turn on the current you see the spark leaping across between the terminals. Sparks of this kind were much studied after the invention of the first electric machine about 200 years ago, which produced them, and I will now show you some peculiarities of these sparks.

Once a spark has passed through the air and broken it down, it so alters the molecules that it makes it easier for another spark to follow in its wake. Instead of the knobs we take two vertical wires parallel to each other and connect them with the terminals of the coil, and turning on the current you see the spark begins at the bottom of the wires and each succeeding spark takes place higher up than the previous one; in this way, you have as it were, a ladder of flame. The reason is that the decomposed parts of air by reason of the heat produced by the spark, rises a little and forms an easier path for the succeeding spark. The conducting power of the air is so greatly increased that the spark will sometimes prefer to follow the path of this altered air in preference to metal, which is such an excellent conductor of electricity.

It is only natural that experimentalists should have wondered how this electric discharge would behave if it was allowed to pass through a vessel from which the air had been pumped out. Faraday, I think, was the first to call attention to the peculiar appearance of the electrical discharge in rarefied air. In the 13th Series of his Experimental Researches on Electricity, 1838, he observes :—

"I will now notice a very remarkable instance in the luminous discharge, accompanied by a negative glow, which may perhaps be correctly traced hereafter into discharges of much higher intensity. Two brass rods 0·3 of an inch in diameter, entering a glass globe on opposite sides, had their ends brought in contact, and the air about them very much rarefied. A discharge of electricity from the machine was then made through them, and whilst that was continued the ends were separated from each other. At the moment of separation a continuous glow came over the end of the negative rod, the positive termination remaining quite dark. As the distance was increased, a purple stream or haze appeared on the end of the positive rod, and proceeded directly outwards towards the negative rod, elongating as the interval was enlarged, but never joining the negative glow, there being always a dark space between. This space of about $\frac{1}{16}$ or $\frac{1}{20}$ inch was apparently invariable in its extent and its positive relation to the negative rod, nor did the negative glow vary. Whether the negative end were inductric or inducteous, the same effect was produced. It was strange to see the positive purple haze diminish or lengthen as the ends were separated, and yet this dark space and the negative glow remained unaltered."

You may look upon this as the first step towards the discovery of X-rays.

De la Rue, Müller, Gassiot, Spottiswoode and Geissler, all did excellent work in studying electric discharges through vacuum tubes. After the discovery of the mercury pump by Dr. Herman Sprengel the degree of exhaustion of these tubes was rendered far more perfect. Professor Hittorf had done some very fine work in Germany with these highly exhausted tubes, and then Sir William Crookes, in this country, did his remarkable researches between 1874 and 1875. By carrying exhaustion to a higher degree than had ever been previously attained, he came to the conclusion that the particles of air remaining in these highly exhausted tubes behaved so differently from an ordinary gas, that he considered it to have attained a fourth condition of matter, which he called *radiant matter*, so that we could no longer only speak of solids, liquids and gases, but had to include radiant matter. The gas in the tube assumes this condition when the vacuum is about a millionth of an atmosphere ; in other words, if a tube is broken and air is allowed to rush in through the opening, there is about a million times more air in it at the ordinary pressure than was the case before the opening was made. When we pass a discharge through such a tube from the negative or cathode side, a stream of particles starts, and anything upon which they impinge is made to glow. This cathode ray has the capacity of producing great heat; it will make platinum red hot, and even melt it; it will cause substances to fluoresce and phosphoresce; it will only travel in straight lines, it will not turn round corners, and it is deflected by a magnet; it will cast shadows of any solid substances placed in its path.

All these observations had been made by Crookes, and necessarily created much interest. Dr. Philip Lenard, in 1894, endeavoured to bring the cathode rays outside the tube into the open, and as glass was opaque to them, he endeavoured to make an opening for them by introducing a small window of thin aluminium foil opposite the cathode. He succeeded, for the rays which passed through his aluminium window produced fluorescence. They affected a photographic plate. He found that they would pass through thin sheets of aluminium, and even of copper; he also found them to affect a photographic plate through metal.

Professor Röntgen of Würtzburg took up the subject where Lenard left it. When I had the pleasure of an interview with Professor Röntgen, shortly after his discovery, I asked him what intention he had in his mind when he commenced the research. He said that he was looking for any invisible rays that might be produced from a Crookes' tube. The next question I asked him was, why had he used a screen of Barium platino-cyanide. He replied that he had used this substance because, by its brilliant fluorescence it was capable of revealing the invisible rays of the spectrum. He then told me that he had covered the Crookes' tube with black paper, so that when it was excited by the electric current no visible light was seen, but he suddenly observed that a piece of cardboard, which had been covered with crystals of Barium platino-cyanide, glowed brilliantly. I asked him what he thought when he saw this. His reply was, "I did not think; I experimented." He showed me the original screen with which this great discovery was made, and I suggested that such an historical screen should be carefully protected in a glass case, and I trust that my suggestion has been carried out.

He speedily found that various substances interposed between a Crookes' tube and a fluorescent screen allowed the rays to pass through in varying degrees, and doubtless he was immensely surprised and interested to observe that when he interposed his hand, that his bones inside his flesh were revealed on the screen. One of the earliest experiments which he tried was to take a photograph through a deal door between two of his laboratories. He placed the tube on one side of the door and affixed to it a strip of platinum, and at a corresponding part on the other side of the door he placed a photographic plate. He then excited the tube by the electric current, and then developed the photographic plate. He found the image of his strip of platinum, as he expected, but he also found a second strip which he could not explain. On examining the door he found that the unexpected strip came to be opposite the beading. It was a pine door, varnished but unpainted. At first he wondered whether the additional thickness of the beading would account for the unexpected strip, but he found wood so transparent, that this view was untenable. He then removed the beading from the door. The explanation was then obvious. Some white lead had been used to cement the strip to the door, and it was the white lead which by its density had caused the shadow on the photographic plate.

It is remarkable that Professor Röntgen, in his original communication concerning the X-rays, described almost all the properties which they are known to possess. Very little, indeed, has been added during these seven years. The chief advance has been in the methods of their application to surgical and medical work.

I will now explain how the X-rays take origin in a Crookes' tube. This rough model illustrates the path of the cathodal stream by means of these cords. A curved cathode, similar in shape to an ordinary reflector, is made of aluminium. The cathode rays emerge from it normal to its surface and converge towards a point, then proceed for a short distance in a straight line, and then gradually diverge—*wherever this cathodal stream impinges upon solid matter X-rays take their origin.* From what has been previously said, it would naturally occur to you that X-rays must have been produced long before they were discovered. This is so. Looking backward, we now know that Crookes in his researches must have been producing X-rays from his tubes. Lenard, no doubt, had X-rays intermingled with the cathode rays which he had so laboriously got outside his tubes. In the early tubes which Röntgen used, the cathode stream was allowed to impinge upon the bottom of the glass tube. The consequence was that the X-rays took origin from a more or less large surface, and consequently the photographs produced by a tube of this kind were necessarily rather blurred; but Professor Jackson, of King's College, London, suggested putting in the interior of the tube a metal anode, inclined as you see in this modern tube, and in this way the converging cathode stream from the concave cathode impinged upon the platinum target, giving rise to X-rays richly from a comparatively small point or surface. This model served to illustrate what happens. The slide now thrown upon the screen illustrates the importance of the proper distance of the anode from the cathode. It should be so placed as to meet the cathode stream at its narrowest part. The impact thus gives rise to a rich production of X-rays from a point, and sharp shadows on the fluorescent screen or photographic plate are thereby produced.

A matter of some practical importance is that all parts of the tube which fluoresce green give off X-rays to some extent. And while a sharp shadow of an object is being cast on a photographic plate by the point on the anode, a blurred image is being produced from the large and diffuse area of the bulb. These rays from the glass may be called secondary, and photographically are about six to ten times weaker than the primary rays.

A strip of lead ½ inch wide and too thick to let any X-rays pass through, was applied closely to the tube—it cast a shadow—no primary X-rays could reach the plate within the shadow; but the two halves of the fluorescing glass supplied diffuse X-rays, and the slide shows two shadows of a single wire interposed.

To cut off the superfluous rays which fog and blur the true X-ray image I surround the tube with non-conducting opaque material—red lead, red lead and plaster, or place it in a box lined with a mixture of white and red lead with a small hole in the lid to act as a diaphragm.

The properties of X-rays may be very shortly summed up as follows:—they proceed in straight lines from their point of origin on the anode to the destination, be it a photographic plate or a fluorescent screen. They are invisible. They cannot be refracted, and they cannot be reflected, except to a small extent, and then only a scattered reflection, just as light is reflected from white paper. They cause certain substances to fluoresce. (This screen was kindly made for me by Messrs. Johnson and Matthey.) They darken a photographic plate; they pass through substances in the order of their atomic weights, the lighter and less dense the substance, the more readily do they pass through, and therefore all organic substances are comparatively transparent, while metals are more or less opaque according to the thickness; they also have the power of discharging electrified bodies. The tube when worked by a coil with a rapid interrupter is illuminated continuously, and the eye gets the impression that the emission of X-rays is continuous, just as the emission of light from a candle, but the impulse of the coil is intermittent, the impact of the cathodal ray is intermittent, and the output of the X-rays is intermittent. If we reduce the speed of the break the light in the tube is seen to flicker, if the speed of the break is increased the light apparently becomes continuous. This is due to a limitation in the human eye. If an impression of light is given to the eye, however transient, it lasts for one-tenth of a second, and if the impressions are repeated oftener than ten times a second, the impression upon the eye is that of a continuous illumination. The intermittence of the highest rate of speed is shown by the rapid rotation of a small fluorescent screen. This experiment shows that the light produced in the fluorescent screen is also transient. This luminescence is in marked contrast to the lasting luminescence which is termed phosphorescence.

During Lord Rayleigh's recent lectures here on Saturday afternoons on recent Electric Developments, I was much interested in his method of producing a very sudden break in the primary of the coil by dividing a wire by a bullet fired from a pistol. He showed that the sudden break gave the full-length spark in the coil without using a condenser. I at once tried the effect of this discharge through an X-ray tube and found that a very brilliant illumination of the tube took place sufficient to take a photograph (show photograph on the screen). It then occurred to me that if I interposed the revolver nozzle with the wire in front of it, between the tube and the photographic plate, that possibly a flash from the X-ray tube would be quick enough to cast a shadow of the bullet in its flight on the photographic plate immediately after the division of the wire had taken place. This I accomplished (show slide on the screen). The shadow of the bullet is blurred showing that the X-rays flash had lasted too long, and this in marked contrast to the beautifully sharp photographs taken of bullets by Professor Boyd by means of the discharge Leyden jar. I repeated this experiment with a revolver with a muzzle velocity of 800 feet per second, and found in two independent negatives that the track of the bullet was approximately the same length and had begun at the same distance from the broken wire. With a Mauser pistol the muzzle velocity being 1400 feet a second, I failed to get an image of the bullet within 10 inches of the stretched copper strip, but got several blurred images of this copper strip, which on this occasion I used instead of wire; the vibrations produced in the broken strip giving rise to many shadows according to its varying positions. The results of the experiments go to show that with the revolver which had an initial velocity of 800 feet a second wherever oscillations may have been produced in the coil, the duration of the X-ray flash was about $\frac{1}{2000}$ of a second. I will now show you the flash in the tube interposing the fluorescent screen by dividing this wire by the pistol, which I now show you. I advise you to close your ears so that the noise may not interfere with your observing the flash.

We now pass on to the action that X-rays have upon the photographic film. Röntgen rays while producing changes in photographic plates in many respects similar to light yet differ in some important respects. For example, I have here six films. In the dark-room they were placed in a bag superimposed like a pack of cards. I put my fingers upon the films and gave a short exposure to the X-rays. The films were numbered, the top one numbered one and so on, and the last one numbered six. On developing these films all in the same way, hardly any difference could be detected, the first and last were almost equally good, so that the X-rays do only partial work in producing a photograph, although the first film produced a firm strong negative, yet sufficient rays pass through and do equally good work on the films below.

There is one advantage in this that in cases where one is doubtful of the exposure, two or more films can be placed together and if the exposure be correct two negatives are obtained, and if the exposure has been too short by accurately superimposing the films a picture of sufficient density could be obtained. But there is another and more striking difference between the action of light upon a photographic film and X-rays. Before saying more upon this matter I will take a photograph by means of X-rays now. In this paper bag there is a plate 20 inches by 24 inches. It is laid upon the table and upon it is placed a metal design. The tube is now placed above it, and, excited by the coil, produces X-rays. The metal stops the passage of the X-rays reaching the films, but all the part not covered by the metal receives the X-rays, because the paper envelope though being quite opaque to light is transparent to the Röntgen rays. The usual proceeding after the exposure is made is to take the plate into the usual dark-room and develope it in the usual way, but I think it would be more interesting to you if I developed this plate before you in this room. I therefore, now that the exposure is complete, take it out of its coverings, and it is now being exposed to this brilliant electric light, and no doubt many suppose that with this excessive exposure to ordinary light that the X-ray picture will be fogged out and spoilt. But I hope that this will not be the case. I now put it in the developing dish and allow the developer to flow over it in the usual way, and if this experiment is as successful as the rehearsal ones have been, I think you will see the photograph gradually appear. The picture you see is the reverse of the usual X-ray negative; in the ordinary negative the part of the film that has been protected by an opaque substance appears naturally white because the silver salts are dissolved out by the fixing solution; after development in this case the metal part is black and the unprotected film is comparatively light. As far as my scanty leisure will allow I have carried out a few experiments testing the effect of X-rays and light combined upon various kinds of photographic plates, and the explanation of what you have witnessed is given by a slide which I will now show upon the screen. It is a remarkable fact that if a photographic plate be exposed to ordinary light for a considerable time and then exposed to X-rays for a definite time, that the effect is entirely different to what occurs if the order is reversed, that is to say, if a plate is previously exposed to X-rays for a definite time and then to ordinary light.

The next slide is from a negative where the exposures to X-rays and to light were made in strips at right angles to each other. You will notice the reversal produced by the X-rays throughout, the combined action of X-rays and then light making the film lighter than the separate action of either. It seems to me that these curious effects are well worth a systematic investigation. [Slide; it came up ordinarily, and then suddenly reversed and remained as now shown.]

I am pleased to be able to express my thanks to Dr. Findley, for his help in carrying out some of these photographic experiments.

Localisation.

I must now leave the physical side, and proceed at once to tell you something as to the surgical application of these rays in locating bullets, etc., in the human body. From what we have seen this evening, you will readily understand that an X-ray photograph is simply a shadow of the object interposed, and the appearance of a single photograph, however realistic, gives no reliable or accurate guide as to the actual relative position of the parts. An X-ray photograph is simply a central projection. It soon became necessary, when the use of X-rays became more general in surgical practice, that some means should be adopted to give reliable data for the position of bullets, needles, etc., in the body. Various plans have been suggested, but the one which I shall describe to-night is the one with which I am most familiar, and one which gives results as accurate as possible. The method may be shortly described as follows:—The anode of the Crookes' tube is placed vertically above a point where two stretched wires intersect each other at right angles. The vertical distance is measured and noted down. The tube is attached to a holder which slides along a horizontal bar, and this bar is carefully arranged parallel to one of the wires. The tube is then displaced 3 centimetres to one side of the zero, a scale on the horizontal bar enabling this to be done correctly. The part of the patient to be photographed is now placed upon the cross wires, which are usually stretched over a space covered by stretched calf-skin. The wires may be brushed over with some aniline dye, so that the mark of the cross wires may be left upon the patient's skin. The photographic plate is now placed beneath the cross wires, and pressed tightly against the parchment. One exposure is made. The photographic plate is then removed and a fresh one put in its place; the tube is then brought back to zero and moved 3 centimetres the other side, and a second photograph is taken. These two photographs will show a parallactic displacement, as they have been taken from two points 6 centimetres apart, approximately the distance between our two eyes; they will not be exactly alike, and if, for example, we were locating a needle in the hand, the different position of the needle in each photograph in relation to the cross wires can be at once shown by taking a tracing from each negative, with a sheet of celluloid with a cross marked upon it. The celluloid is put upon the photographic film, and the cross upon it is brought into register, that is, superimposed over the shadow of the crossed wires in the negative. A tracing is then made of the needle, and the same is done with the other negative, and it will then be found that the needle images occupy different positions. To interpret this I use an apparatus called a cross-thread localiser, which enables a graphic reconstruction of the conditions in which these negatives were taken.

The cross-thread localiser consists of a large sheet of glass with two lines scratched upon it at right angles to each other, and crossing at the middle point. A small T-piece of metal with three notches in it is supported on a vertical rod, and can slide up and down. It is so arranged that the three notches are in a line parallel with one of the diamond scratches, and three centimetres separate the centre notch from the adjacent ones on either side. The tracing from the negatives on the celluloid is placed upon the stage with the crosses superimposed. The metal support, with the notches, is then fixed so as to be the same height from the stage as the anode was from the cross-wires. The two lateral notches now represent the two positions to which the anode of the Crookes' tube was respectively displaced, and as X-rays travel in straight lines without deviation, fine threads can be used to trace their path. Therefore if a thread, attached to a needle, is placed upon the end of the tracing of one of the needles, and a thread through the other notch is placed upon its own shadow at a corresponding point of the needle, the threads will intersect, and the point where they intersect represents the actual position in space of that end of the needle. Now the distance of this point of intersection from the photographic plate is the actual depth of that point below the surface of the patient's skin next the photographic plate. If a perpendicular plane be raised upon each of the horizontal wires, and the vertical distance from each taken, we get three measurements which enable us, from the markings of the cross on the patient's hand, to fix a point upon his skin beneath which, at a known depth, the foreign body is certain to be found. In geometrical language, we get three co-ordinates of the point in relation to three planes at right angles to each other, and as the relation of the patient's body to these planes is also known, it is a simple matter to decide the actual position of the needle or other foreign body; more than that, the size and shape of the foreign body can be ascertained. But these two photographs, while enabling this information to be derived from them of ordinary triangulation, are really stereoscopic, and when viewed in a Wheatstone's stereoscope by an observer possessing binocular vision, the eyes will triangulate the negatives, as it were. The negatives should give a combined image in perfect stereoscopic relief, so that by this method not only can actual measurements and data be given to the surgeon, but a view of the parts be also afforded. As an indication of how reliable this method is, I will mention that I have applied it in detecting very minute particles in the eyeball and orbit in a great number of cases, and this proves of signal service in eye surgery. I have detected and located in the eyeball particles of glass, steel, brass, iron, copper, silver and lead. The method for localisation is based upon the same principles.

In warfare as well as in civil life the X-rays when properly used are of invaluable service, and I consider that the stereoscopic method is of the highest value in giving the maximum and accurate information that could possibly be afforded by X-rays. Several examples of stereoscopic skiagrams are exhibited in the Library, and I am glad to state that there is also exhibited there an instrument for obtaining the stereoscopic image directly on the fluorescent screen.

On two occasions at the Soirée of the Royal Society I have exhibited apparatus for giving the stereoscopic picture on the fluorescent screen, but, while interesting, they were too cumbersome for practical use. The problem to be solved mechanically was quite definite. Two tubes had to be placed opposite the observer's two eyes, the distance between the anodes preferably should be the same distance apart, namely about 6 centimetres, as the distance between the observer's two eyes. A fluorescent screen interposed midway had to be illuminated by one tube, and the shadow of whatever object was cast upon the screen had only to be observed by one eye, the other being eclipsed, then the next tube had to be illuminated and then the other eye only had to see the shadow produced by it. If this alternating arrangement could be repeated quicker than ten times a second the impression of the two shadows becomes continuous in each eye, the consequence being that the combined mental image stands out in striking stereoscopic relief. This diagram shows the principal features of the instrument which I am exhibiting in the Library. I have to thank my friend Dr. Muirhead for the help he has given me in the construction and designing of this instrument. A previous one was made for me by Mr. Crawley, representing Messrs. Muirhead, but which depended for its action upon two synchronous motors, but the latter instrument with the oscillating eye-piece is likely to supersede the former.

The practical value of getting a clear and brilliant stereoscopic image upon the screen is immense, for not only are the parts seen in their correct position, but when the apparatus is properly arranged, it is possible for the observer, with a metal probe, needle or forceps, to touch any object he desires which he sees in the stereoscopic image.

[J. M. D.]

LONDON: PRINTED BY WILLIAM CLOWES AND SONS, LIMITED
GREAT WINDMILL STREET, W., AND DUKE STREET, STAMFORD STREET, S.E.