BRITISH MEDICAL JOURNAL

LONDON SATURDAY DECEMBER 11 1943

PHYSICS AND THE SURGEON*

BY

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William Wood Bradshaw, whose memory this lecture honours, was born in 1801 and became a member of our College in 1833. He was a man of unusual enterprise, for in the same year he became a Doctor of Medicine of Erlangen, and his appreciation of education was further shown when in 1844 he matriculated at Oxford as a Gentleman Commoner of New Inn Hall, becoming a Master of Arts three years later. He practised as a doctor in Reading, and in 1854 this College showed its high opinion of his worth by electing him a Fellow as a Member of 20 years' standing. He died in 1866, and his widow endowed a lecture at each of the Royal Colleges "to maintain her husband's name in good repute by associating it with the advancement of the science which he loved, and to testify her gratitude for the happiness which she owed to him." I feel that William Bradshaw was a man we should all like to have known and whose memory we gladly honour. He was an ornament to the College, and I am grateful to our President for the opportunity he has given me of following his own memorable Bradshaw Lecture of 1940.

It has been customary to choose as a subject for the Bradshaw Lecture some aspect of surgery which has interested the speaker for much of his life, which is of general interest to his colleagues in the art of surgery, and which is not without interest to the layman. In choosing as my subject Physics in Relation to Surgery I have entirely satisfied the first condition, and I hope to satisfy the other two. It is of course a vast subject, and I can only touch on a few of its fields; of these I have chosen Force, Heat, and Radiation as branches of physics which affect the surgeon most closely and which he is constantly turning to his own use. But even in these I must limit myself to a few problems with which I have met in surgical work and upon which some knowledge of physical principles has thrown light, sometimes revealing important features that would otherwise have been missed.

Force and Movement

Two of the most important subjects considered in physics are Force and Movement, and of these we have endless examples in the human body. The movement, of course, occurs at the joints, and the force is exerted by the muscles; but few of us are aware of the forces which the muscles can exert, or appreciate the exquisite precision of the mechanism by which the movements are controlled. The best examples are always obtained from one's own experience, and I cannot choose a better illustration than one from an exercise of which in years gone by I had ample experience—the pulling of an oar. From our standpoint it is a very simple action and lends itself to accurate measurement, though from the oarsman's point of view it is anything but simple. Seated on a sliding seat and driving with his full power from the stretcher, he can exert a drive

of 400 lb. weight. As his seat moves freely it follows that through each of his legs he exerts a driving force of 200 lb. Let us see how this is accomplished.

Although apparently so simple, the movements involved are by no means simple and the forces employed are exceedingly complex. The most important movement, however, is the straightening of the knee, and the muscle effecting this is the quadriceps extensor. Now in my own case, while the slide travels 18 inches my patella travels only 3 inches, or one-sixth of the track of the slide, and therefore if the quadriceps alone did the whole of the work the force exerted by the quadriceps on the patella would be six times the driving force exerted by the leg, or 1,200 lb. This is an exaggeration, as other muscles act indirectly, and noticeably the gluteus maximus in extending the hip; but I should be well within the mark in saying that my quadriceps alone can exert a force of 600 lb., and that the whole of my thigh muscles acting together can exert a total force of half a ton. Moreover, these great forces have to be exerted with the utmost delicacy, for the watermanship which controls the balance of a racing boat depends upon differences in the pressure of the toes measured in ounces.

Now the modern treatment of a fractured femur is to reduce the fracture to an accurate position by traction, and it is usually found that a force of 15 lb. is quite sufficient. How do you account for such a ridiculous disparity? To talk about tiring out the muscles is absurd, for the effect on the patient's comfort is immediate. What really happens is that the irritation arising from the fracture is checked, the reflex which produces spasm of the muscles is broken, the muscles relax, and it is on the relaxed muscles that traction is exerted. It is of importance that this point should be remembered when the powerful methods of modern skeletal traction are employed, and its neglect has often resulted in failure of a simple fracture to unite.

In order that such a small force should be effective it is essential that the limb should be slung quite freely so as to avoid friction, and if this is done the traction force has a secondary result, to which it is worth while to call your attention. There must, of course, be some counter-pull to prevent the patient being pulled out of bed, and this is most easily obtained by raising the foot of the bed. But you will see at once that this counter-pull acts on the centre of the pelvis, while the traction pull passes through the hip. This side of the pelvis is thus pulled down so that the pelvis lies obliquely and the leg is effectively abducted at the hip. In the case of a fractured femur this is of no importance, but in many conditions of the hip-joint abduction is the essential point in treatment. You might imagine that this would easily be obtained by swinging the leg out; but this is by no means the case, as the pelvis may swing with it. Traction in the line of the leg is the correct physical method of obtaining abduction; but this simple fact is not generally appreciated, and the so-called abduction splint is still too often seen, even—low be it spoken—in the wards of orthopaedic surgeons. Moreover, traction in the line of the femur can abolish pressure

* The Bradshaw Lecture, given before the Royal College of Surgeons of England on Nov. 11, 1943.

on the hip-joint, and in the case of inflammation in the joint this may effect the immediate abolition of reflex spasm and the dramatic relief of the patient. Direct attempts at abduction will increase the pressure and, by increasing spasm, make abduction impossible.

One of the most interesting muscles in the body from the physical standpoint is the biceps muscle of the arm. As its name implies, it arises by two heads from the scapula; it lies in front of the humerus, to which it has no attachment, and is inserted into the back of a tubercle on the inner side of the radius. Its action is thus a very complex one, and the provision of a single muscle for this very complex movement is a measure of its importance. It rotates the forearm outwards, it flexes the elbow, and it flexes the shoulder; and it thus achieves the most important of all human movements, for it enables us to bring food to our mouths.

But for the moment I would direct attention solely to one element of this movement—the rotation of the forearm. The very powerful movement of supination is effected by two muscles, the biceps and the supinator brevis, both acting at what we term great mechanical disadvantage and the biceps taking the larger share. By holding a weight at the end of a rod and raising it by rotating the forearm it is easy to measure the force involved and to show that the biceps tendon, which is no bigger than a shoelace, can easily support a tension of at least 100 lb. weight.

But the biceps does far more than merely provide a powerful force, for by its nervous connexions it measures the amount of force and adjusts it to requirements, and at the same time it acts as a delicate feeling piece, defining exactly the degree of its contraction and giving most precise information as to the position of the limb. How superbly the muscles perform this function can be seen in the facility with which a pianist can strike a distant note with absolute certainty and without the aid of vision.

The position of the hand and arm produced by contraction of the biceps, supination, and flexion of the elbow and shoulder is of particular interest, as it is that adopted by the violinist and the fencer, and, far from being an abnormal position, it is that in which the fingers and the whole limb are under the most perfect control. I do not suppose that it has ever occurred to a violinist that it is to his biceps that he owes the possibility of maintaining the position of his left hand. Still less would it occur to him that the peculiar action of the *right* hand in drawing the bow, described as raising the wrist, is essentially based on a rotation of the forearm, again controlled by the biceps. Rotation of the forearm is indeed a movement of countless uses, and one over which it is possible to develop the most exquisite control.

Another muscle whose mechanism has always fascinated me is the opponens of the thumb. This little muscle is capable of exerting great force, and with the adductor pollicis forms the basis of a powerful grip. But the beauty of its action consists in the *rotation* which it gives to the thumb so that this may face the object grasped. Whatever the size of the object—a large ball, a ring, a pencil—it will be found that the pulp of the thumb faces the object and ensures a powerful and yet most delicate grasp. It is one of the most perfect examples of adaptation to function in the human body.

Force and the Skull

So far we have considered the forces exerted by the human body. Let us now consider the forces it is capable of resisting, and as an example let us consider the effects of a blow on the head. If a man were struck on the head by a stone weighing 1 lb. and falling a distance of 9 ft., he would probably have some degree of concussion, although his skull might not be broken. Let us consider the forces involved. The stone falling 9 ft. reaches a velocity of 24 ft. per second, and as it weighs 1 lb. it has acquired 288 foot-second units of energy. If it deforms the skull one-quarter of an inch, which is about the possible limit, it means that the resisting force has destroyed this amount of energy in $1/48$ of a foot, and the average force must therefore be 48×288 units of force, or 432 lb. weight. If this be distributed over an area of the skull $2\frac{1}{2}$ in. in diameter it would mean a local pressure of 86 lb. to the square inch.

Now, the skull is for all practical purposes filled by an incompressible fluid, which for such sudden forces has no escape. Any deformation will be resisted by a rise in intracranial pressure, and the effect of this will be enormously greater than any resistance offered by the comparatively elastic skull. Thus the rise in intracranial pressure in the case we have described will be at least in the order of 80 lb. to the square inch. Such a pressure, even though it lasts only for a fraction of a second, must force every drop of blood from the capillaries and leave the brain completely anaemic, with the clinical result of a complete and instantaneous paralysis. Surely this provides a complete justification of Trotter's theory that the phenomena of concussion are the result of sudden anaemia resulting from the rise in intracranial pressure. So far as I am aware he never actually calculated the pressure, but the surmise is an example of the penetration of his intellect. No more acute brain than that of Wilfred Trotter has ever adorned the College—like a diamond in the keenness of its penetration, in its crystal clearness, and in the sparkling brilliance of its humour, as he himself was like a diamond in the flawless perfection of his character.

My attention was first directed, many years ago, to the problem of intracranial pressure by a curious case which came under my care at the London Hospital. A child of 3 years had been knocked down by a light cart, the wheel of which passed over her head. She was unconscious and had a large and very dirty lacerated wound of the scalp above and behind the right ear. I cleaned the wound up as well as I could, and in doing so noticed a fine crack running vertically through the centre of the temporal region. The condition of the child precluded any further disturbance, and indeed I was astonished two days later to find that she was fully conscious and in very fair condition. Then, however, she went back, and at the end of four days from the injury was comatose, with clear signs of intracranial pressure. Expecting to find an intracranial haemorrhage, I trephined and discovered beneath the hairlike crack not blood but an extradural disk of hard mud, 2 in. in diameter and $1/4$ in. thick in the centre. I removed the mud and left the skull widely open. To my amazement the child made an uninterrupted recovery.

Now, the considerable mass of mud can only have got in through the crack, and as the force applied was but momentary, the crack must have opened widely. If one may estimate the momentary force as 250 lb. weight, this would be supported only by the pressure within the skull, for the skull of a child is far too fragile to offer appreciable resistance to such violence. If, further, we regard the child's skull as a sphere 5 in. in diameter and imagine it to have been flattened by the compression of the wheel over an area $2\frac{1}{2}$ in. in diameter, as would seem a reasonable approximation, we find that the force of 250 lb. weight must have been supported on an area of 5 sq. in., so that the pressure within the skull must have been 50 lb. to the square inch. Now the central cross-section of a sphere 5 in. in diameter is just 20 sq. in., and as the internal pressure, although momentary, is exerted equally in all directions this means a disruptive force of 1,000 lb., or nearly half a ton, so that the wide opening of the crack is fully explained. That such forces must produce anaemia is obvious; that the brain should recover shows how little even the most delicate cells are affected by mere pressure and that in every case its most important effect is to deprive them of their blood supply.

The Absorption of Heat

A very interesting problem in physiological physics, and one with practical results of the first importance, is introduced by the application of heat to the surface of the body. As a simple example let us consider what happens if the forearm is placed in a tank of flowing water at 110° F. If the forearm were a mere mass of inert flesh its temperature would rapidly rise to that of the water; but that this does not occur is shown by a very simple experiment which I owe to Sir Thomas Lewis. If while the arm is immersed in the bath its circulation is checked, in a few seconds the feeling of comfortable warmth gives place to intolerable pain, for the deep layers of the skin are too sensitive to stand such a temperature. With an intact circulation the vessels of the skin rapidly dilate and the heat is carried off by the blood stream,

so that the temperature within the limb is prevented from rising to a painful level. The temperature in the deep tissues does, however, rise to a certain degree, and in response to this the vessels dilate and the blood flow increases. This necessarily results in increased metabolism and an internal production of heat in the limb.

An elaborate protective mechanism is thus brought into play, depending for its effectiveness upon an intact circulation, and in this the skin plays a predominant part. The skin protects the deep tissues in two ways. When it is cold and avascular it forms an efficient defence against the loss of heat, without which one could survive in a cold sea only for a very short time. When it is warm its vascularity increases enormously, so that the blood flow may be a hundred times as great, and it now protects the deep structures by the amount of heat it can carry away in the blood stream.

If, however, owing to local pressure or some defect in circulation the flow of blood in the skin is diminished, this protective mechanism breaks down and the temperature of the skin itself, or even of the deeper structures, may rise to such a point that coagulation and local death of the tissues occur. This is undoubtedly the explanation of many of the hot-water-bottle burns, especially under anaesthesia and in patients with defective circulation. It is the explanation also of necrosis arising in another circumstance, in which the connexion is far less obvious.

Endothermy is one of the most valuable gifts of physics to surgery, and with reasonable precautions and in skilled hands it would seem to be perfectly safe. It consists in the passage through the body of a high-tension current which oscillates to the order of a million times a second—so rapidly, in fact, that none of the chemical effects of electricity occur in the tissues. The current, however, is comparatively large and may reach as much as three amperes, so that a great amount of heat is produced by the resistance of the tissues; and it is characteristic of endothermy that, as the name implies, the heat is produced *in* the tissues. If, for example, the two poles of the apparatus are held in the hands the only sensation is one of peculiar warmth inside the wrists and spreading up the arms.

Now, provided that the heat is carried off by the circulation so that the local rise of temperature is not excessive no harm results. If, however, this condition is not satisfied terrible disasters may occur. It is quite common to place the so-called indifferent pole under the sacrum, and unless a large soft pad is used it is obvious that the pressure on the thin skin in this region may render the skin avascular, so that its temperature may rise to a dangerous point. But this is not all. The sacrum itself has a poor blood supply and is not very sensitive, so that even in a conscious patient its temperature may rise dangerously. I know of two cases in which it underwent total necrosis. The risk of such a disaster is very real, and the indifferent endothermy pole should never be placed in this position. In fact, wherever it is applied care must be taken that the blood supply of the tissues is adequate and not obliterated by pressure; for unless this condition is satisfied extensive necrosis of the skin may occur.

The increased metabolism which arises from the heating of the tissues introduces considerations which show how dangerous it is to regard the body as a mere piece of physical apparatus, and this is especially the case where there is a defect in the circulation. If heat is applied to a limb in which the circulation is so defective that it cannot respond to the demands made upon it, gangrene may be precipitated. If, on the other hand, heat is applied to some other part of the body no harm can be done, since heat can only be conveyed to the damaged limb by its circulation, and increase in this can only be beneficial. In a case, therefore, of incipient gangrene heat may be applied to any part of the body other than the affected limb, where only the loss of heat should be prevented.

Similar considerations apply in certain cases of shock; for if the body is heated when the amount of circulating blood is inadequate the resulting vasodilatation and increased metabolism may actually result in a further lowering of the blood pressure, with even fatal results. The supply of heat is justified only when it has been established that there is an adequate amount of blood in active circulation.

Radiation

I would turn now to another branch of physics of recent development, the implications of which we are only just beginning to realize. Radiation is of course one of the oldest of physical studies, for it is radiation which brings to us the heat, energy, and light of the sun; but it would not be too much to say that its developments in the last 25 years have revolutionized our lives. To it we owe the wireless waves which allow us to speak and to listen across the world. X rays are only one of its forms, and it is to radiation alone that radium owes its power.

The radiation of which I am speaking consists of ether waves transmitting energy across space at a uniform velocity of 186,000 miles a second, so that the light of the sun takes just 8½ minutes to reach us across 93 million miles of space. No matter what the wave-length of ether waves their velocity is unaltered, but the physical effect of the radiation depends on the wave-length. In order to appreciate the vast range of wave-lengths at our disposal, one may make a diagram in which the whole range of 60 octaves which we use is illustrated graphically by objects of similar dimensions. At one end of the scale we have the very long waves, each of which might reach from here to Aberdeen; and then we have the ordinary wireless waves ranging from 2,000 metres to as little as 10 metres—a range of about 8 octaves. Heat waves come next, occupying a short region of wave-lengths from one-hundredth to one-thousandth of a millimetre; and then comes the single octave which gives us light. For this octave alone are we provided with any sense organ capable of appreciating the vibrating energy by which all space around us and within us is filled. To this octave we owe our perception of the beauty of form and colour by which we are surrounded, and without it the blue sky, the rolling clouds, the green fields, and the infinite variety of Nature's shades would for us no longer exist. One wonders what the other octaves might reveal could we but perceive them.

Beyond the light octave come the ultra-violet rays, and, far beyond these, x rays and the gamma rays of radium, the last so short that one hundred thousand would be required to equal one wave of yellow light.

Now, it is a fundamental law of radiation, although it was discovered by Planck but a few years ago, that it can only exist in certain units of energy and that the energy in each unit is inversely proportional to the wave-length: thus the unit of energy for hard gamma rays is one hundred times that of ordinary deep x rays and a hundred thousand times that of yellow light. It is to this that such rays owe their penetrating power and their effects upon the tissues. The shorter the wave-length the greater the energy, and in exact proportion; so that to compare the unit of energy from radium with the unit of visible light is to compare a 12-in. shell in full flight with a pellet from an air-gun.

X rays and the gamma rays of radium have now taken their place as established instruments of surgical technique, but to understand their use it is essential to know something of their origin and nature. Both arise within the atom, but from very different sources.

In the modern view all matter is built up of atoms, and each atom of any one substance has an identical structure, whilst all atoms are variations and elaborations of the same general pattern. Each atom consists essentially of a nucleus round which circulate a number of electrons, themselves minute and identical particles of negative electricity. Hydrogen is the simplest of all atoms, consisting only of a nucleus and one electron. Helium has a larger nucleus and two electrons, and the atoms of the elements gradually increase in size until we reach uranium, with a vastly complex nucleus and a cloud of 92 electrons flying around it. Radium itself is nearly as complex with 88 electrons in its service.

Radiation arises from disturbance of the electrons in their orbits and from their attempt to regain their normal positions. As one might expect, the possible radiations of any given element are strictly limited, and to this it owes its spectrum. Every element has its own peculiar spectrum or group of lines, each of which represents one wave-length of radiation, the whole forming the signature of the element by which its

presence can be detected with absolute certainty even in the furthest star. Various forms of disturbance can give rise to radiation, and the commonest is, of course, heat, the source of most of the spectra with which we are familiar.

There is, however, a much more powerful way of arousing the electrons to radiate, and that is by hurling at the atom a stream of electrons driven by strong electric forces, and it is in this way that x rays are produced. The result is a radiation of short wave-length, perhaps one ten-thousandth of that of light and of corresponding energy. To obtain such results a modern x -ray plant may require half a million volts—a really terrific force comparable to that of a flash of lightning. It is a wonderful achievement that we are able not only to produce such vast physical forces but to control them and to bend them to our service.

The gamma rays of radium arise also from a disturbance of the electron field of the atom, but this disturbance is produced not by any outside influence but by an explosion of the nucleus of the atom itself. For reasons of which we are entirely ignorant the nuclei of the atoms of radium explode at regular intervals at an absolutely uniform rate of roughly one atom in a million per day. As a result, another substance—the gas radon—is formed, the atoms of which again explode but at much shorter intervals, and this process is repeated until there is left only an inert particle of lead. The whole process is described as “decay,” and it is not too much to say that the discovery of the decay of radium by Becquerel revolutionized all our conceptions of matter.

These successive explosions of the nucleus in the process of decay produce a violent disturbance of the electron field of the atom, and as a result a radiation is produced of very short wave-length and enormous energy. The radiation is thus identical in kind with that of x rays, but of x rays produced by an energy of two million volts. Moreover, such x rays would require a huge engineering plant for their production, while the gamma rays are given off in a continuous stream by the most minute particle of radium.

Now it has been found that such radiation of short wave-length and great energy had a profound effect upon the tissues, and especially upon cellular growth. Where the cells are dividing rapidly they may be completely destroyed, and it is this property which gives these rays their peculiar value in the treatment of malignant growths. In such growths the cells are always dividing at a rate many times, sometimes thousands of times, more rapid than that of normal cells, and it is just this rapid division which marks them as vulnerable to x rays and gamma rays.

But it must not be imagined that the normal tissues are immune. They are profoundly affected, and the greatest skill is required to destroy a growth by radiation without doing irreparable damage to the tissues in which it lies. Some sacrifice is unavoidable, but it should be only such as can in time be remedied by the natural processes of repair.

Of the exact mechanism by which the radiation produces its effect upon the cell we know almost nothing; but it must certainly be atomic, and the primary effect must be the ionization of certain atoms and a consequent rise in their chemical activity. Some substance is thus produced which is toxic to the cell, or perhaps some substance is destroyed which is essential to its normal growth. It would seem to be upon the chromosomes and upon the reproductive mechanism of the cell that the effect is most severe, for it can be shown that the cells which survive and continue to reproduce are themselves deformed and transmit their defects to succeeding generations.

It is evident that in radiation we possess a powerful but very dangerous weapon, for though it may destroy a malignant growth it may do incalculable damage to the tissues which remain. Moreover, if the growth is not completely destroyed and reappears it will now spread in the tissues damaged by radiation, with annihilating effect. I believe that in radiation we have one of the greatest weapons of surgical progress; but it is indeed a weapon and not a tool, and only those who are prepared to devote their lives to its study have any right to use it except in very limited fields or with the close co-operation of those who understand its dangers as well as its powers.

Conclusion

I have ranged over a very wide field and yet I feel that I have only touched the fringes of my subject. I hope that I have convinced you that there are many points at which the work of the surgeon enters the field of physics and that towards the solution of many of the problems of surgery the physicist could give invaluable help. I trust that the future may see a fuller collaboration between two branches of science which at first seem to have little in common and that each may gain from the experience which the other brings.

THE HUMAN RESPONSE TO FLYING STRESS*

BY

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LECTURE II: THE FOUNDATIONS OF CONFIDENCE

Fearlessness

In this lecture I shall consider the nature of fearlessness, by which I mean a state of mind in which fear is absent under circumstances which would naturally be expected to arouse that emotion. I should make it clear at the outset that I distinguish fearlessness from courage. The latter is a state of mind in which fear is present, but is endured for the sake of attaining an object. Fearlessness, as the word implies, is a state in which there is no need for courage because fear does not exist. Fearlessness in relation to a particular stimulus pattern may be primary—meaning that no fear response has ever occurred; or secondary—meaning that the fear response was at one time present but has since been lost. Reverting to what has been said of the origin and growth of fear reactions in children, we may postulate causes for fearlessness of the first kind. First, certain trigger responses may be lacking owing to constitutional variation. Secondly, the process by which the original trigger responses normally develop, so that they respond to a wider range of stimulus patterns, may be interfered with. This process may be called learning, or in Pavlov's (1927) terms the development of conditioned responses, and may be interfered with in a number of ways. Broadly speaking in terms of conditioned response, we may distinguish between processes which depend upon variations in the efficiency of the cerebral cortex as analyser and those which result from variations in experience and training. For either of these reasons there may be failure to acquire those fear reactions which most people do acquire as the result of conditioning.

Thus there is a kind of fearlessness which is associated with lack of intelligence or imagination. Fearlessness of this origin may be a source of strength in time of danger, but carries with it a source of weakness. The same defect of brain or mind which prevents the acquisition of fear by conditioning or experience prevents the inhibition of fear by conditioning or experience. Thus the stupid man is fearless in the presence of remote or complex danger, but in the presence of immediate obtrusive dangers he is apt to be more overcome by fear for the moment than others of greater intelligence. Nevertheless the man whose lack of imagination prevents anticipatory fear is thereby saved much stress.

That training and experience, or lack of experience, may affect the range of fear reactions is theoretically obvious and commonly observed. The factors involved are numerous and complex. Parental example and influence are clearly of great importance, and begin to operate so early that it must be very difficult to trace their origins. It is possible that an inhibitory process may in some instances anticipate the development of a positive conditioned response, or even, as Valentine (1942) suggests, that inhibition may be so well established on some other foundation that an unconditioned fear response destined

* Based upon the Dunham Lectures at Harvard University, March, 1943, and the Croonian Lectures before the Royal College of Physicians of London, May, 1943.