

## THE DEVELOPMENT OF HEAT BY MUSCULAR ACTIVITY.

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It is the object of physical science in the proper sense of the word, to perceive in all the phenomena of nature the operations of the *same* forces, with which any two material particles always act upon each other, when they come in contact with each other in the same relations. This object has never been so clearly seen by the majority of naturalists, as during the last decade. Since that time a law already proved in mechanics has been recognized as one applicable to all the events of nature. It is called by Helmholtz, who in a treatise which appeared thirty-one years ago, first demonstrated its universal importance, the "law of the preservation of power"; recently the designation "law of the preservation of energy" has also been brought into use by English men of science. The amazing productiveness of this fundamental law of the operation of all natural forces essentially consists in the fact that from it may easily be derived experiments for testing results even in natural phenomena, in which in detail the nature of the acting forces is wholly concealed.

Therefore it could not fail to happen, that since this time individual investigations in the most varied departments of physical science have principally turned upon this fundamental principle. It now seems to me that the results of such individual investigations, which are connected with the most universal points of view, might be best adapted to secure interest even outside the circle of the scientists. In this opinion I will venture to claim the attention of the readers of this publication for some general observations connected with an experiment made by me a short time ago, and elsewhere communicated to persons familiar with such matters.

Each individual in experience in his own body at any moment, that with the aid of his muscles he can conquer opposing forces and set masses in motion. The former happens, for instance, when we lift a burden or throw the whole weight of the person upward in climbing a mountain; the latter occurs when we hurl a stone or swing a hammer. The principle of the preservation of power now demands that, where we see forces conquered or masses moved, necessarily powers on the other side have "acted" or performed labor, that is, that the points of assault of forces have been displaced. This, for instance, is clearly apparent in the voluntary fall of a heavy body. It is the point of attack of a power directed downward, namely weight, and as under the influence of this power it moves downward, its velocity increases; or when in a wavering balance one scale with its burden ascends—its weight is conquered—but the other sinks and its weight performs a certain amount of work. So it by the mediation of muscular action we see forces conquered or masses moved, it must be asked: what powers have acted or performed the labor here, that is, have changed their points of attack in their action.

Forces which, for instance, like weight, act upon larger bodies in a similar manner, will not of course be alluded to here. The point in question can only concern powers that operate even among the smallest particles of muscular substance, that is chemical powers of attraction. Something must take place in the muscle similar to what occurs in the steam-engine, when in the act of combustion under the boiler the particles of carbon and oxygen, obeying their strong reciprocal power of attraction, rush towards each other, making violent little movements, and a portion of this energy, by means of a series of shocks, is applied to the conquest of opposing forces, or to accelerating the speed of bodies. So in the muscle, during its activity, chemical processes evidently take place, with which powerful kindred forces come into action. That this is really the case can be shown by experiments. Singularly enough, it is not only an analog-

ous, but for the most part at any rate precisely the same chemical power of attraction which performs the work in the active muscle and in the steam-engine, namely the power of attraction between the particles of carbon and the particles of oxygen. The product of the operation of this power of attraction, carbonic acid, appears in a certain quantity at every act of muscular motion.

In all the examples, in which, by the mediation of any arrangements, through whose operation the action of chemical powers of attraction, taking place even in extraordinarily small distances, accelerates the movement of bodies, or overcomes mechanical forces, like weight, a general remark may be made, which has hitherto been everywhere confirmed by experience. The lines of communication between the particles undergoing a change by means of a chemical process are usually irregularly distributed in every part of the space. The movements arising from the individual processes of change are, therefore, also irregularly driven in all directions, and thus can never be applied in their full strength to overcome an opposing force acting in a fixed direction, or to accelerate the speed of a body, whose particles are all moving in the same direction. Only a portion of this collected energy of motion can appear in such a form. A fraction, greater or less, according to circumstances, of the sum of the individual processes of change must retain its original form of the irregularly whirling movement of the tiniest particles. This conclusion may, therefore, be briefly expressed thus: wherever in a chemical process the power of attraction of the smallest particles of different substances performs labor—no matter under what circumstances this may occur—a portion of the labor will always be employed in the development of *heat*.

The *heat* contained in a body is, therefore, nothing else than the energy of slight invisible irregular whirling movements, in which the tiniest particles of the body are included. To increase the temperature of a body, therefore, is merely to increase the energy of these irregular molecular movements of the smallest portions. This view instantly finds support in the common phenomenon, that at the increase of the temperature of a body above a certain degree its particles in consequence of the colossal energy of motion really pulverize each other—"the body evaporates."

If this view of heat is correct, a certain degree of heat can be produced by a certain amount of work. The proportion of work, or the operation of a power is, as is well known, the product of the intensity of the power and the distance through which it has acted. Therefore the product of the unit of the intensity of the power, the *kilogram*, and the unit of the distance, the *meter*, is chosen as the unit of this power. This unit of the value of the work is called the *kilogrammeter*. As the unit of the quantity of heat the same degree has been fixed that is required to be supplied to a kilogram of water, when its temperature is to be raised from 0 to 1 of the Centigrade.

Natural philosophy has now succeeded—and it is one of its most important achievements—in showing, that for the production of a unit of heat an expenditure of work of 425 kilogrammeters is requisite. This number is called the *mechanical equivalent of heat*, because it is thereby possible to calculate each quantity of heat in a certain number of mechanical units of work, which is requisite for its production.

The knowledge of the mechanical equivalent of heat enables us to measure exactly the work performed by any chemical process of kindred forces operating even at immeasurably little distances, although we know nothing at all of the laws of action of these forces in detail. In fact, we need only direct the process, so that no effect is produced except the development of heat. If we then measure the heat developed and multiply the number of units found by 425, we shall have the labor which the chemical powers of attraction have performed in the process, expressed in kilogrammeters, since according to the

supposition the whole operation of this labor consisted exclusively in the development of heat. The burning of one kg. of coal may serve as an example; if no other effects are accomplished, about 8000 units of heat will be released. The work which the kindred powers between the atoms in one kg. of coal and the two-fold number of atoms of oxygen accomplish in their union into carbonic acid, thus amounts to  $8000 \times 425$  or 3,400,000 kilogrammeters. From this an idea may be formed of the prodigious intensity of the chemical power of attraction between an atom of carbon and an atom of oxygen. The force with which the particles of carbon, amounting only to one kg., rush from a very little distance to the corresponding particles of oxygen in burning, is precisely as great as when a body weighing 3,400,000 kilograms falls from a height of 1 m.

Let us go back with these axioms from natural philosophy in general to muscular action. If, as was shown, there are chemical powers of attraction, whose operation or performance of labor produces mechanical effects which are externally perceptible, besides these, heat must also proceed from every muscular action. This proposition, which we here bring forward as a conclusion from the most universal lessons of the action of powers, has already long been acknowledged as a principle derived from experience.

It was by no means easy to prove this proposition. To be sure, it is rendered extremely probable by the daily experience, that our bodies are perceptibly heated by great muscular exertion, and give off more heat than during the same time with the muscles at rest. But this does not afford an accurate proof. It might be represented that the excessive activity of the muscles only afforded increased opportunity for heat-producing combustion in other constituent parts of the body, for instance in the blood. An exact proof can, therefore, only be given by putting in action a muscle severed from connection with the rest of the body, and proving that heat is developed therein. Such experiments can, of course, only be made on the muscles of cold-blooded animals, because those of the warm-blooded, when separated from the body, lose their vital properties too quickly.

The first person who made such experiments and has shown an increase of temperature, that is a development of heat in *isolated* muscles by action, was *Helmholtz*. This fundamental fact could not fail to attract great attention, and make people endeavor to ascertain what circumstances had an influence on the greater or less development of heat by muscular action. The most important labors in this direction proceeded from *Heidenhain's* laboratory. He has especially much improved the thermo-electric system, which alone can be used to ascertain the increase of temperature of the muscles. With the aid of this system one can distinctly perceive even the extraordinarily slight increase of temperature, which a little frog muscle undergoes at a single, by no means energetic, movement, that scarcely amounts to  $\frac{1}{1000}$  of a Centigrade. In successive experiments it can even be determined, in which *more*, and in which *less*, heat was developed, but until now the system has not been thoroughly adapted to fix the absolute value of the increase of temperature.

Some time ago I succeeded in so changing the thermo-electric apparatus, that it is possible, by its means, to fix with some degree of accuracy, the increase of temperature a muscle experiences in its action. Thereby the possibility was instantly afforded, of stating in the usual units the quantity of heat developed by the muscular action. This quantity of heat is namely, evidently, the increase of temperature multiplied by the capacity for heat of the proportion of muscle used, which latter is assumed to be about equal to  $\frac{1}{10}$  of the capacity for heat of a body of water of equal size.

According to a general observation previously made, the whole labor performed in the muscular act by chemi-

cal powers of attraction can now be definitely determined. For this purpose it is only necessary to allow the muscular action to pass away, so that finally no sort of mechanical effect remains; then, since every labor of forces must leave an effect, a quota of heat will exist that will be the exact equivalent of the work performed by the chemical powers. The condition just expressed may be fulfilled by simply letting the muscle, in its action, raise a weight; but allowing this to fall again, so that it pulls the muscle which meantime has relapsed into a state of rest. In so doing the work performed by the weight of the falling body will evidently be used for the development of heat in the apparatus. To be sure, it might now be asked, in what portions of the whole machinery used, this amount of heat is developed. Theoretically it is beyond doubt, that a portion of it is set free in the intermediate pieces, which connect the weight with the muscle, especially by the friction at the points of union, but since these intermediate pieces are practically non-ductile, and the friction at their points of union can only be very slight, it may be assumed from the beginning, that the quota of heat in question is almost entirely released in the body of the muscle itself, which, by its extreme ductility, receives, so to speak, almost entirely the shock of the falling burden. This supposition is so probable, that in the exact scientific publication of the result of my experiments, I have pre-supposed it as a matter of course. Meantime I have made experiments in my laboratory, which render this supposition one empirically shown.

The experiments have been made in the following manner. A body of known weight fastened to the muscle was raised, not by its own action, but by other labor to a measured height and then allowed to fall. The increase of temperature experienced by the muscle in consequence of the jerk was now measured, and by multiplication with the capacity for heat of the muscle, the quantity of heat developed in the muscle was ascertained. It usually corresponded in a really surprising manner with the thermic equivalent of the mechanical labor, which was applied to raise the appended burden. This affords the proof, that the heat produced by such a jerk is liberated almost entirely in the *muscle*, and only very inconsiderable fractions are developed in the other portions of the machinery used. Every such experiment can thus be looked upon as fixing the mechanical equivalent of heat, which, of course, in point of accuracy, falls far behind the purely physical tests, but is worthy of notice because a living tissue is the means of ascertaining it. To us, however, the interest of these experiments consists in the fact that they prove the reliability of the system used to fix the heat of the muscles.

Let us now return to the development of heat by *active* muscular action, and consider more closely the numerical product of an accurate experiment. That in the estimates of the quantities of heat, and afterwards the value of labor too, many ciphers may not appear immediately behind the comma, we will base them upon units a million times smaller. So, for the unit of heat, we will take the quantity of heat necessary to raise the temperature of 1 mgr. of water from 0° to 1°. As the unit of labor we will choose instead of the kilogrammeter the grammillimeter. The equivalent proportion, therefore, remains unchanged—425. For an experiment a body of muscle weighing 3114 mgr. had lifted in ten pulls, rapidly succeeding each other, a burden of 500 gr. 10 times, and the latter had fallen again as many times, so that at last it hung no higher than at first. The temperature of the mass of muscle was increased 0.0195° by this act. Now, since 3114 mgr. of muscular substance possesses exactly as much capacity for heat as 2803 mgr. of water, the increase of temperature which followed, required  $2803 \times 0.0195 = 54.6$  units of heat. But in our experiment the production of this quantity of heat is the *only* effect of the work accomplished by the chemical powers of attraction in the muscular action. It must, therefore, ex-

pressed in the measure of labor, have amounted to  $54.6 \times 425$ , that is 23205 grammillimeters.

The chemical process, which takes place in muscular action is, it is true, by no means accurately known in the individual stages of its course; but as a whole, it undoubtedly consists in the combustion of a body free from nitrogen, whether fatty or saccharine, to carbonic acid and water. The numbers obtained, therefore, afford us a point, by which to determine what quantities of the above mentioned materials must be consumed in a muscular contraction. We know, through *Frankland's* researches, that in the consumption of 1 mgr. of sugar the chemical powers of attraction perform as much work as is necessary to produce 3800 units of heat. Now, since in the ten contractions of our experiment, 54.6 units of heat were produced, an expenditure of material of  $54.6 \div 3800 = 0.014$  mgr. would have been necessary, under the supposition, that the combustible material was a saccharine body. Let us suppose that the combustible material is a fatty body, then a still smaller expenditure would be sufficient, to produce the effect observed, namely,  $54.6 \div 9000 = 0.0067$  mgr., because 1 mgr. of fat, according to the estimates of the investigator just mentioned, supplied in its combustion, 9000 units of heat. So, for one contraction the combustion of 0.0014 mgr. of sugar, or of 0.00067 mgr. of fat, would have been requisite. If we divide this number by 3.1 (the weight of the quantity of muscle used in grams) the result will show how much material must be consumed at *one* energetic contraction in a gram of muscular substance, that is 0.00045 mgr. of a saccharine, or 0.00022 of a fatty combination. So it appears, that for 1000 energetic contractions not quite 1 mgr. of combustible material in each gram of muscle is requisite, and, therefore, it can no longer surprise us, that only very small quantities of the actual combustible material are ever found in the muscular substance, the greater portion of which, as is well known, really consists of very different materials, principally of substances like the white of an egg.

The results obtained with the new systems can be applied to the decision of the question, what portion of the work performed by chemical powers in the active muscle, can, in the most favorable cases, produce mechanical outward effects. The closest interest in this question might be designated as an "economical" one. In fact, the real object of the animal subject in muscular activity is the production of mechanical effects in the surrounding universe, and one might denote the portion of the work accomplished by chemical powers, which is applied to the mere production of heat, as an inevitable loss from the point of view of animal economy. At any rate, one will have the more reason to admire the judicious arrangement of the muscular substance, which can apply a larger portion of the chemical labor performed in it to external mechanical results.

It is precisely the same as in the steam-engine, whose construction we also call the more perfect, according to the larger portion of the work performed by the chemical powers of attraction in the burning of the coal it allows to be used to produce mechanical effects. In spite of the most eager efforts of technics hitherto no attempt has been successful in making more than  $\frac{1}{10}$  of this labor mechanically effectual. Fully  $\frac{9}{10}$  are lost to the objects of the machine, by being inevitably employed in the production of heat, which at the utmost can only be used for minor purposes, such as the heating of rooms and similar objects.

If it must now be ascertained, how the muscle is situated in this respect, it is only necessary to fix, by experiment like the one above described, what mechanical effect has been accomplished in a given time, and compare this measured in the proportion of work, with the chemical labor calculated by the heat produced. It will be advisable to pay special attention to the fact, that the heat finally developed would be less by a corresponding

amount, if the experiment had been so arranged, that the mechanical effect, that is the raising of the weight, had been maintained. The quantity of heat corresponding with this effect was first released in the muscle by the falling of the burden again.

By the 10 contractions of the foregoing experiment 500 gr. were raised on an average about 1.3 mm. high. Thus the mechanical result amounted in the whole to 6,670 grammillimeters. The work performed by chemical powers of attraction in the 10 contractions we have found above—23,205 grammillimeters. This number is about  $3\frac{1}{2}$  times 6,670. Thus, by these contractions, somewhat over  $\frac{1}{4}$  of the whole chemical labor was applied externally and not quite  $\frac{3}{4}$  to the direct production of heat. That in the actual experiment this quarter was also finally converted into heat, depended merely on the external arrangements, which permitted the burden raised to fall again each time.

We see by this, that—as was to be expected—the muscle machine is very superior to even the most perfect steam-engine, in so far that it *can* employ the combustible material twice as frugally for the same main object.

Besides, this relation between mechanical action and development of heat is by no means obtained at *every* muscular contraction. I have intentionally selected from my experiments as an example, the one in which the mechanical labor amounts to the largest fraction of the whole chemical labor. To obtain this most favorable proportion, the burden must stand in a certain relation to the thickness of the muscle. If the burden is larger or smaller, a smaller portion of the chemical work will be used for mechanical action, or—as it might be expressed—the combustible material will be less economically used. This proposition may be demonstrated *a priori*, for it is easily seen, that in the two extreme cases, where the burden is a cypher or infinitely great, chemical work is performed and heat developed, but no external mechanical action is obtained.

The solution of the question, in what relation the mechanical action for the development of heat can stand, under the most favorable circumstances, towards the muscular contraction, enables an observation to be made which throws new light upon the change of substance in animal bodies. As is well known, the change of substance in animal forms may be designated in general as a process of combustion. In reality, a certain quantity of combustible nutritious matter daily enters into the fluids, and a corresponding quantity of oxygen is taken in with the breath. On the other hand, every day on an average, a precisely similar quantity of substances is withdrawn, whose combination is to be regarded as the product of an almost total combustion of the nutritious matter. The condition of the body with this equal balance between receipts and expenditures, remains for a long time apparently unchanged.

With the formation of the product of combustion from the assimilated nutritious matter and the inhaled oxygen, the colossal power of attraction of this element for the elements of the nutritious matter, especially for the carbon and hydrogen gas, now performs a fixed amount of labor, which is independent of where the combustion takes place, and whether it occurs at once or in various stages at various places.

People were formerly inclined to suppose, that the greater portion of the combustion in question occurs either in the fluids themselves or in special organs, such as the liver, the kidneys, etc.

Since the changes occurring in animal bodies have begun to be viewed from the standpoint of the principle of the preservation of power, it must be looked upon as a self-evident truth, that at least a certain portion of the assimilated nutritious matter passes into the muscles, to be first consumed here, since from the point of view of that principle, the mechanical performance of the muscles can only be understood as the action of the labor of the

chemical powers of attraction, as we have done in the preceding discussions. The question may now be raised, how large a fraction of the whole combustion takes place in the muscles, and how large a fraction in the other parts of the body? The distribution of the process of combustion in the different places might, therefore, be accomplished in two ways. One part of the material might be consumed entirely in the muscles, the other entirely elsewhere, or certain stages of the combustion of the whole material might take place in the muscles, and other stages in other places. However this may be, as it is supposed that a considerable portion of the combustion takes place outside of the muscular substance, it must be expected that, under all the circumstances, far more than  $\frac{1}{2}$  of the whole heat of the combustion of the assimilated nutritious matter in animal bodies appears as heat, and only the equivalent of far less than  $\frac{1}{2}$  is available for mechanical labor. For, as we saw, even under the *most favorable* circumstances, about  $\frac{1}{3}$  of the chemical work performed in the muscle itself is inevitably used for the production of heat. But under these most favorable circumstances, however, probably *all* the muscles do not take part in the labor of the whole body. Therefore, in the acts of living beings we must assume that more than  $\frac{1}{2}$ , probably  $\frac{2}{3}$  of the result of the work performed in the muscles by chemical powers, finally appears as heat. Now, if the material coming into the muscles for combustion should be even a moderate portion, for instance  $\frac{1}{3}$  of the whole assimilated nutritious matter, while  $\frac{2}{3}$  was consumed elsewhere, then  $\frac{1}{3}$  of the chemical work performed by the whole combustion is used for the mere production of heat, since  $\frac{1}{3}$  of the labor accomplished outside of the muscles can have only the result of producing heat, and of the third coming from the muscle,  $\frac{1}{3}$  will also produce mere heat. So, under this supposition, it must be expected, that at the utmost the equivalent of  $\frac{1}{3}$  of the heat proceeding from the combustion of the nutritious matter would be available for the mechanical effects of the organism, externally.

It is already more than twenty years since Hemholtz, by very convincing arguments, proved from facts known at that time, that in seasons of extreme muscular labor, for instance, climbing a mountain, the measureable mechanical performances of the whole organism are proportionally considerably greater. They are equal to the equivalent of about  $\frac{1}{3}$  of the heat of the consumption of the material that burns during the time of these performances, in the whole body. Unless the supposition is now made, that the muscles of mammalia can work incomparably more economically than the muscles of the frog—a supposition wholly unjustified by our knowledge of the properties of the muscular substance in the different bodies of animals—we must conclude that, in times of extreme muscular activity, the whole process of combustion takes place in the muscles and the chemical processes going on in other parts can only be those in which the chemical powers of attraction accomplish no considerable labor. In fact, from the results of our experiments concerning the heat of the muscles we have inferred, that by the chemical labor performed in the active muscles themselves in the movements of living beings, fully  $\frac{1}{3}$  is employed in the production of heat; but if chemical labor was performed in other parts of the body, whose whole result could be only a purely thermal one, more than  $\frac{1}{3}$  of the chemical labor performed in the whole body must go to the production of heat, and less than  $\frac{1}{3}$  would remain for mechanical external actions.

If it is once proved, that in times of extreme muscular action the processes, by which the chemical powers of attraction perform labor, take place almost exclusively in the muscles, a similar performance will occur even in times of comparative muscular rest; for otherwise it must be supposed, that the change of substance during the period of rest takes a totally different direction from that during the time of muscular activity, which is scarcely conceivable. Yet it must be supposed, that in animal bodies a certain kind of combustible material is prepared for the machin-

ery of the muscles, for which in other portions the conditions of combustion do not exist, as coke cannot be burned in a stove arranged for wood. We shall, therefore, be compelled to suppose, that the process of combustion, which renders muscular labor possible, glimmers continually in this texture even in times of rest, only with so little strength, that there is no mechanical action, and only heat is produced.

There is a very note-worthy harmony between this inference and an assertion made by Pflüger and some of his pupils on the basis of very different facts, which is, that in the muscles, even during periods of rest, processes of combustion occur, which are under the influence of the nervous system; they can be kindled to considerably higher degrees of intensity, before attaining the point requisite for the purpose of a visible mechanical action of the muscle. The increase in the department of these lower degrees of power would, therefore, lead only to an increase of the production of heat, and according to the well-founded hypothesis in question ought to explain the fact, that the development of heat in animal bodies can exist under conditions of the loss of heat externally.

From all this one would form the following idea of the course of the chemical processes, by which the assimilated nutritious matter is transformed into the rejected matter. The nutritious matter enters into the blood, the liver, and other places only during the chemical processes in which the chemical powers of attraction either perform no considerable work, or in which as many chemical powers of attraction are conquered as come into positive action. These may be partly synthetic performances, partly disjunctions. Above all, it must be supposed that the greater portion of the nutritious albumen undergoes, directly after its reception into the fluids, a process of this nature, in which a body containing nitrogen is separated, that soon leaves the body under the form of urine. The remnant of the nutritious albumen, free from nitrogen and the other nutritious matter rich in carbon and hydrogen, is then supplied to the muscles as combustible material, perhaps loosely united with the oxygen received by the breath. In action, however, the vast powers of attraction between the atoms of oxygen on one side and the atoms of carbon and hydrogen on the other, first enter into the muscular tissue, whereby in the formation of carbonic acid and water, partly heat and partly mechanical effects proceed.

I should consider the object of these lines attained if I succeeded in showing how a few insignificant thermometrical experiments in frogs' muscles are capable, from the point of sight of the principle of the preservation of power, of casting a new light on all the particulars of the nourishment of the human body.—*Translated from "Deutsche Rundschau," by M. J. S.*

DR. T. S. COBBOLD exhibited (at the Linnean Society's meeting, November 5) under the microscope about a hundred eggs of *Bitharzia hamatobia*. They were taken from a gentleman who had just arrived from Egypt, and who was the victim of hematuria, supposed to have been contracted during a shooting expedition. By adding water nearly all the eggs were hatched during the meeting of the society, and a rare opportunity was thus afforded of witnessing the behavior of the newly-born ciliated animalcules.

DONATION TO AID SCIENCE. Mr. Charles Crocker has made the very handsome donation of \$20,000 to the California Academy of Sciences, the income of which is to be devoted to aid worthy and studious investigators in any branch of science, who, by their scientific work, have excluded themselves from acquiring support through the ordinary avocations of current industrial life.

M. PAUL BERT, the new French Minister for Public Instruction, is said to be a candidate, in the section of Medicine, to fill the place vacated in the Academy of Sciences by the recent death of Dr. Bouillaud.