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Cordeiro, Frederick Joaquim Barbosa, 1859-
Augustus Long Health Sciences Library

Publication/Creation

Brooklyn, N.Y., [1897]

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THERMICS

AND

Thermo-Dynamics of the Body.

BY

F. J. B. CORDEIRO, M. D.,
P. A. Surgeon, U. S. Navy.

From THE SANITARIAN *for July, 1897.*

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NEW YORK

BROOKLYN, N. Y.

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THERMICS

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THERMO-DYNAMICS OF THE BODY.

By F. J. B. Cordeiro, M. D., P. A. Surgeon, U. S. Navy.

The animal kingdom, in regard to heat, can be divided broadly into two classes—cold-blooded animals and warm-blooded animals. The former conform to the temperature of their suroundings, their vital-chemical reactions taking place with nearly equal facility through a wide range of temperatures. The latter possess a certain definite temperature which they maintain at all times and which may be considered a life function of the species. The difference is entirely one of equlibrium.

All bodies, whether living or dead, must lose or gain heat from the surrounding medium according as their temperatures are higher or lower than that of the medium. In cold-blooded animals this loss of heat is greater than the production, and consequently an equilibrium is not reached until the temperature of the body has nearly coincided with that of its envelope. In warm-blooded animals, on the other hand, since life can exist only within certain narrow limits of temperature, the expenditure and gain of heat must at all times be nicely balanced. Under different conditions it will be seen that the members of such an equation may vary widely, though the equality must always be maintained. The body, then, can be considered a thermostat set to a certain vital temperature.

In studying the movement of heat in a body it is essential to know the specific heat, the penetrability and permeability to heat, of its various parts. Such constants have unfortunately (so far as the writer knows), not been determined for living bodies or for most animal tissues. The total quantity of heat in an idividual would be the sum of the specific heats of its parts multiplied by their masses, into the absolute temperature, which we may consider as 310. The average specific heat of the body might be determined by observing the quantity of heat given out by a dead body in cooling between two fixed temperatures.*

The writer, for his own satisfaction, has made certain observations regarding the thermal constants of animal tissues, but since proper facilities were lacking, they can be considered scarcely more than surmises. In dealing with the problems shortly to be taken up it will be necessary to have some idea in regard to these constants, and the following determinations will serve to fix our ideas. According to certain measurements the specific heat of the blood is somewhat less than that of water, though considerable. Its conductivity may be considered as sensibly equal to that of water. This is as we should expect, since it is composed so largely of water (90 per cent.), and the direct consequence is that, owing to its unceasing circulation the body has a very high permeability (interior conductivity). Whatever heat or cold is received externally or internally is quickly diffused throughout the body and the internal equilibrium is nearly maintained at all times. Not that the temperature of the body is everywhere exactly equal, for such is not the case. The exterior is hotter or colder to a slight extent than the interior, according as the surrounding medium is above or below the vital temperature. Certain parts also, during activity, may be warmer (muscles, glands), and as we shall see later, cooler (lungs), than the neighboring parts, but in general the average temperature is preserved nearly uniform.

We see then that the blood, owing to its high specific heat, conductivity and rapid circulation, is eminently fitted for receiving large quantities of heat (or cold), and distributing it. It thus performs the function of maintaining the internal equilibrium.

According to certain rough determinations the specific heat of the proteids is relatively small, that of muscle being perhaps .08 of water, while that of the bones is less. Of the solid tissues fat stands alone as possessing a very high specific heat, perhaps equal to that of blood, while its conductivity is small. We may thus make an estimate of the thermal capacity of the body as possibly one-third that of water, though in the absence of exact determinations this can be considered as scarcely more than a guess. As fat is mainly situated directly under the skin, it would seem, from the foregoing properties of storing large quantities of heat and parting with it slowly, to be eminently adapted to keeping the sur-

*On the plausible supposition that there is no marked difference between the specific heats of living and dead tissues.

face warm and preventing rapid losses at the exterior. However, rapid losses may take place at the suface under the following circumstances. The skin, which in itself may be supposed to have a very small penetrability, is extremely vascular, and when a large volume of blood is flowing, we may say, in contact with the surface, it may give out or absorb a considerable amount of heat according as this surface is hotter or colder than the surrounding medium. The coefficient of penetrability of the surface may therefore vary from a very small to a very large quantity. It has been observed* that, on exposure to a low temperature, the naked body loses heat from the surface at first rapidly, but that soon the peripheral circulation ceases almost entirely; the skin becomes blanched and, paradoxical as it may seem, the bodily temperature rises above the normal. In this case it is plausible to suppose that the considerable reduction of the expenditure of heat caused by the cessation of the surface circulation causes a temporary storing up of heat. It will be seen subsequently that under the circumstances there is an increased production of heat, due to compression of air in the lungs, so that the increase of temperature is readily acounted for. The writer has also found that by immersing the body in hot water (41°) there was at first a rapid absorption of heat by the body† (200 calories per second), but that shortly the surface became blanched, showing a cessation of the peripheral circulation, and that under similar conditions of temperature, the amount entering the body from the water (due allowance being made at all times for the loss to the air), became too small to be measured.

The exterior of the body is then, composed of a cushion of fat, itself non-vascular and pierced by a few large blood vessels which ramify extensively directly in contact with the surface.—This cushion of fat has a high specific heat and low conductivity. The skin itself has an extremely low conductivity (no direct measurements have been made), but when filled with a rapidly flowing blood current is capable of emitting and absorbing a considerable amount of heat. Such an apparatus is an ideal one for the admission or exclusion of heat according to circumstances. It is extremely desirable that a series of accurate calorimetrical experiments should be undertaken for the determination of the coefficient of penetrability of the skin under different circumstances. We shall see

* Foster. Text Book of Physiology.

† Shown by the cooling of the water, not by increase of temperature of the body.

later on when we consider experiments on an individual exposed to high temperatures, that this coefficient may become very small.

We shall now attempt to write our physiological equation in the language of mathematics and afterwards to translate it. We have seen that for a warm-blooded animal the sum of the heats expended must equal the sum of the heats produced, for that is the condition of life. We shall endeavor first to tabulate the sources of heat in the body and measure these amounts as far as is possible. In its fullest expression such a problem must be enormously complex, but in general terms we may arrive at an approximate solution.

Ultimately all the heat produced in the body is derived from the potential energy of the food ingested. We can easily measure the total energy of a certain amount of food, but this energy is used by the body in such varying proportions and at such varying rates that little benefit would accrue to our present problem from such an investigation.

An important source of heat in the body is due to the friction of the blood as it circulates in its vessels. All of this resistance, which is overcome by the heart, is transformed directly into heat. We may calculate the amount approximately. If we suppose that 180 ccs. of blood are expelled from the left ventricle at each stroke, under a pressure of one-third of an atmosphere, this would correspond to .6192 kilogramme-metres at each stroke, and at 72 strokes a minute, this would give 44.3124 kilogramme-metres per minute. If we suppose that the right heart does one-quarter the work of the left, or about 10 kilogramme-metres per minute, we have for the total work per minute 54.312 kilogramme-metres, which corresponds to 128 calories per minute.

This is perhaps a rather high estimate for ordinary conditions, but where, as we shall see later on, the heart is forced to pump a much larger quantity of blood in order to maintain the normal temperature, this estimate is probably much exceeded at times. Since this friction takes place largely in the most constricted portions of the circulation, it would be natural to expect that the blood which had been driven through the capillary system of a gland would issue much warmer than it entered and such we find to be the case. Thus the blood of the hepatic vein has been observed to be 40.73 while that in the right heart was 37.7. In the muscles no contraction can take place without an increased flow of blood through them with a simultaneous constriction of the capillaries, which would naturally give rise to a considerable production of heat—a fact constantly observed.

In the salivary glands during active secretion the saliva may be 1° to 1.5° higher than the blood in the carotid artery. In most text books of physiology this production of heat is explained as due solely to glandular activity (whatever that is), but in view of the preceding discussion we see that a large proportion of it, if not all, must be due to the friction of the blood in the gland capillaries. If a gland during its action performs an anabolism, that is, elaborates a product of a higher potential than the material worked upon, there must be an absorption of heat equal to the potential gained.

On the other hand where a gland secretes katabolically there must be a generation of heat equal to the drop in potential. Considering the muscles as force glands, which in fact they are, there is here undoubtedly katabolism which may be wholly transformed into work, and which would be the case if a muscle were an engine of perfect efficiency. Anabolism also takes place in a muscle, in the heart probably during the return stroke, which would be accompanied by an absorption of heat.

Determinations of the efficiency of muscles, with proper regard for the heat derived from the friction of the blood, have not yet been made. It is probable that a much higher efficiency obtains than is supposed, especially in certain automatic muscles, such as the heart and respiratory muscles which work continually at a constant rhythm.

The heat due to mental activity will not be considered, as it is extremely doubtful if such exists.

To recapitulate, then, we may tabulate as constant and varying sources of heat in the body:

1st. The katabolism of the food.

2d. The friction due to the circulation, which, though varying, may be considered to average about 180 kilogramme-degrees in the 24 hours.

3d. The heat absorbed through the surface when the surrounding medium is of a higher temperature than the body.

4th. The heat due to ingesta when these are of a higher temperature than the body. This includes the inspired air.

5th. Heat due to compression of air in the lungs.

6th. Whenever in external or internal contact with the body, any substance passes from a gaseous to a liquid state (condensation), or from a liquid to solid state (solidification).

It will be noticed that glandular activity is not included in the above list, since the heat generated in a gland is probably either frictional or katabolic.

Next, inquiring into the various means by which heat is lost to the body, we have:

1st. The loss through the surface when the external temperature is lower than that of the body.

2d. Whenever, in external or internal contact with the body, any substance passes from a solid to a liquid, or from a liquid to a gaseous state. Thus solution of salt or sugar in any liquid is accompanied by a definite absorption of heat. When food is dissolved by the digestive liquids, heat is absorbed and the resulting temperature is that due to the liquefaction plus, of course, the potential energy lost when katobolism takes place. The evaporation of water, whether on the surface or in the lungs, is of course attended with an absorption of heat which is equal to the latent heat of vaporization at the temperature of the body. The amount of heat which may be lost by evaporation of water on the skin varies within very wide limits. It depends on the amount of perspiration secreted, or the temperature and relative humidity of the atmosphere and the velocity of the currents of air to which the body is exposed. When saturation of the atmosphere exists and the external temperature is less than that of the body, evaporation can still take place at the surface, but when the temperature of the surrounding medium is equal or greater than that of the body, no evaporation can take place, and consequently no heat can be lost to the body by this means.

3d. Heat may be lost by the warming of ingesta, and this applies to the inspired air. This is only possible when the ingesta are colder than the body, since as we have already seen in the reverse case heat will be gained. It is stated in most physiologies that heat is lost to the body through the expulsion of the urine and faeces, but a little consideration will show that the temperature cannot be affected by this means, while if the substances from which these products are derived were originally ingested warmer than the body there must be a net gain of heat. Accordingly the urine and faeces have no place in our problem.

4th. Heat may be lost to the body by the expansion of air in the lungs during the process of breathing. Let us consider carefully the changes taking place during the respiratory cycle. For the average individual the capacity of the chest at the beginning of inspiration, including bronchial nd nasal passages, is about 3,000 ccs. The tidal air is approximately 500 ccs. This is the amount expired or inspired, and the two quantities are sensibly equal. During each breath there is an interchange of gases between the blood and the air in the lungs, 4 per cent. of the oxygen of the inspired air being transferred to the haemoglobin of the blood, while the partial pressure due to the oxygen is replaced by an equal volume of carbonic dioxide from the blood. Since the loss of pressure from absorption of the oxygen is at each instant made good by a corresponding substitution of carbonic dioxide, we may consider the dynamics of the expansion and compression of the gases in the lungs without regard to these interchanges.

We may liken the action of the chest to the stroke of a piston in a cylinder. Since the orifices by which the air is admitted to the lungs is relatively small to their capacity, it follows that if the expansion takes place faster than the air can rush in we shall have at first a brief period in which the pressure of the air in the lungs sinks to a minimum, when the inrushing air, which increases with the difference of pressure, externally and internally, is at length sufficient to prevent the pressure sinking any lower. This minimum pressure is preserved until the end of the stroke when an equlibrium is again established between the external and internal pressures.

During the return stroke, which is the act of expiration, the pressure is increased in the lungs to a maximum until the rate of outward flow prevents a further rise. This maximum is maintained until the end of the stroke, when by expansion the external and internal pressures are once more brought into equilibrium. Practically, for rapid breathing, we may consider the act of respiration as simply a forward and backward stroke with alternating minimum and maximum pressures, and that no air leaves the cylinder except while the piston is in motion.

What the maximum and minimum pressures in the ultimate air cells are we do not know, but experiments show that in the trachea these pressures are about 70 mms. of mercury above and below the atmospheric, for ordinary breathing. Since the lungs (with exceptions) are emptied quicker than they are filled, there is some reason to suppose that simultaneously with inspiration the bronchioles contract and with expiration relax.* Their structure, the folded

* This may be reversed to obtain peculiar effects of respiration, as we shall see later on.

arrangement of the mucous membrane and the circular muscular fibres surrounding them would seem to support this view.

It is a matter of frequent observation that a warm-blooded animal maintains its proper temperature in a much higher atmosphere for an indefinite time.

It is usually explained that this equilibrium is maintained by the evaporation of the perspiration from the skin with perhaps a certain amount from the lungs. It is true that a large amount of heat is, under ordinary circumstances, so dissipated, and if we suppose the air to be perfectly dry, an unlimited amount of perspiration to be secreted and the body to be exposed to a draught of very high velocity, there is scarcely a limit which can be put to the temperature which the body could not theoretically endure. But if we suppose the atmosphere to be saturated (and of higher temperature), we can have no water evaporated from the skin. But we know that a body, even under these conditions, may maintain its temperature. It is evident that the thermotaxic mechanism can bring about such a result by two means acting conjointly, and only by two means. First the penetrability of the body is diminished, and with it the quantity of heat which enters the body from without. But this is not sufficient. Secondly, there must be an absorption of heat in the body. We shall now see that this absorption is brought about by a peculiar kind of respiration whereby a greater weight of aqueous vapor is expired than is inspired and by the expansion of air in the lungs.

It will be observed that the manner of breathing differs widely under various conditions according as heat is to be absorbed, or economized to the utmost, or possibly to be generated in the lungs. In a Turkish bath, or on a very hot day, the frequency of respiration is much increased, besides having other peculiarities. This can be observed in a shaggy-haired dog on a very hot day, breathing one hundred or more times a minute, the expirations taking place with explosive suddenness. The animal having no surface evaporation is obliged to run his lungs as a cooling machine in order to maintain his temperature. When going into a very cold atmosphere (if naked) the frequency of respirations is much reduced. A deep inspiration (gasp) is caught and the whole air is held compressed in the lungs for a long time before it is explosively expelled and the process repeated. Here, as we shall afterwards see, heat is absorbed to a minimum degree or, when the external and internal temperatures have not too great a difference, heat may actually be gained by the compression of the air.

Dynamically we may consider the residual air as remaining permanently in the lungs (though this is not actually the case), the tidal air flowing in and out with each stroke. The air in the body is in relation peripherally with the respiratory mucous membrane, and centrally it is in the closest contact with the pulmonary plexus. Both tracts are excellent conductors, but the capillaries must be much the better of the two. This capillary conductivity may be still more increased by an increase of the blood stream through the lungs. It will thus be seen that when the lungs are laboring to absorb heat, for the cold so produced—if we may use this reverse phraseology—to be taken up and distributed at a maximum, a certain increased flow of blood is necessitated, and this the thermotaxic mechanism provides by an increased heart action. We see, therefore, that when the economy is struggling to maintain its temperature, increased respiratory activity always takes place concurrently with increased heart activity. When in this struggle the economy finally succumbs, we have seen that where death is not due directly to the disturbance caused by the increasing temperature, it arises from respiratory or heart failure. These failures are to be considered not alone an exhaustion of nerve centres, but of muscular tissues as well. Perhaps the latter is the larger factor.

In the following discussion I shall let P represent the pressure of the atmosphere, T the temperature of the body and ϑ the temperature of the atmosphere. Let p be the minimum, and p_1 the maximum pressure of the air in the lungs during any respiration.

I shall consider first the aqueous vapor in the lungs at different stages of the respiratory cycle. Let the relative humidity of the atmosphere be r. If we suppose a half litre of this air to be inspired at each breath, which is an average amount, it will contain:

$\frac{5}{8} \times \frac{1.293}{2} \times \frac{1}{1 + a(\vartheta - 273)} \times \frac{f\vartheta}{760} \times r = a$ grammes of water, where $f\vartheta$ is the partial pressure of saturated aqueous vapor at temperature ϑ and $a = .00367$.

Let us now suppose that by the return stroke the pressure is raised to p . If this return stroke be executed slowly, the air in the lungs will nearly maintain a temperature T and be compressed isothermally. A certain amount of water will be condensed, but if the return stroke be executed suddenly it will approach towards a limiting condition where the air is compressed adiabatically and the tidal air, since conduction is a function of the time, will be expelled before it has time to part with its heat of compression, or with any of its aqueous vapor. It is to be remarked that the air in the lungs is at all times saturated.

We may suppose that the inspired air at the end of inspiration will have acquired the temperature of the blood, although the expired air may not have time to do so before being expelled, for the following reasons: First, as the inspired air swirls in, it is carried by its momentum inwards against the rapidly flowing blood current, so that the major part of the expired air is the original air in the lungs. Secondly, coincidently with the compression of expiration, the expired air begins to leave the body, so that at any subsequent instant only a fraction of it remains inside the body. Thirdly, the time of inspiration is usually longer than that of expiration.

The mass of the expired air, if oringinally at temperature T and compressed adiabatically from pressure p to pressure p_1, will be raised to the temperature $t_1 = \left(\frac{p_1}{p}\right)^{\gamma} T$, where $\gamma = \frac{k-1}{k}$ and k is the ratio of the specific heat of air at constant pressure to that at constant volume. This mass of air must take up sufficient water to saturate itself at its volume, pressure and temperature.

The weight of water necessary to saturate this mass under the conditions is : $\frac{5}{8} \times \frac{1.293}{2} \times \frac{1}{1+a(t_1-273)} \times \frac{ft_1}{760} \times \frac{Pt_1}{p_1 9} = b$ grammes where ft_1 is the partial pressure of saturated aqueous vapor at temperature t_1. If $b > a$, there must be an evaporation of water at every breath.

We have considered in the above discussion only the aqueous vapor in the tidal air since, the residual air always returning to initial conditions, the sum of the evaporations and condensations must be equal for the complete cycle.

We shall next consider the dynamic changes in the lungs on the supposition that the air is dry. If we suppose the mass of the residual air to be M and that of the tidal air to be m, and that the expansion from p_1 to p, and the compression from p to p_1 is performed so quickly as to be adiabatic, and that at end of inspiration and expiration the temperatures coincide with that of the blood, we may write the quantity of heat extracted by the residual air from the blood during expansion $Ms_p(T - \left(\frac{p}{p_1}\right)^{\gamma} T)$ and that restored during compression $Ms_p(\left(\frac{p_1}{p}\right)^{\gamma} T - T.)$ These quantities will not be precisely the same, since more work is done in the latter case than in the former.

If we suppose the tidal air to be first raised to the temperature of the body and then expanded isothermally, we have as an expression for the heat abstracted from or added to the blood, according to sign, $M\ s_p\ (T - \vartheta) + \frac{PV}{J} \log \frac{P}{p}$, where V is the volume of the tidal air at T, P, and J is the mechanical equivalent of heat. Sp. is the specific heat of air at constant pressure. During the reverse stroke the mass m of the tidal air is compressed, let us suppose, adiabatically from p to p_1. Coincidently with the compression, however, it begins to leave the body. If the conduction were such that this mass if retained inside the body would give up all its heat in the time of the return stroke, it can be shown that when at the end of the stroke no tidal air is left in the body, but one-third of this heat can be given to the blood. As the expulsion of this tidal air becomes more sudden, a limiting condition is approached in which none of this heat is given up to the blood.

Under the conditions specified we can, therefore, write the total heat lost or gained (according to sign) by the blood, $M s_p\ T\left(1 - \left(\frac{p}{p_1}\right)^{\gamma}\right) - M s_p\ T\left(\left(\frac{p_1}{p}\right)^{\gamma} - 1\right) + m\ s_p\ (T - \vartheta) + \frac{PV}{J} \log \frac{P}{p} =$ Q or calling $\frac{p}{p_1} = 1$, we have $2\ M s_p\ T - M s_p\ T\ (1^{\gamma} + 1^{-\gamma}) + m\ s_p\ (T - \vartheta) + \frac{PV}{J} \log \frac{P}{p} = Q$. Assuming for a particular case that $\frac{p}{p_1} = \frac{7}{71}$ and $\frac{p}{P} = \frac{7}{70}$ we find that $2\ M s_p\ T = 441.75$ and $M s_p\ T\ (1^{\gamma} + 1^{-\gamma}) = 445.5$, while $\frac{PV}{J} \log \frac{P}{p}$ is approximately equal to 4 calories. If $\vartheta = T$ we have, therefore, $Q = 445.75 - 445.5$.

We thus see that from the adiabatic compression and expansion of dry air, but little heat can be absorbed during the cycle.

If the expansions and compressions take place isothermally no heat can be gained or lost from the residual air. For ordinary conditions we have seen that about 4 calories is absorbed by the expansion of the tidal air.

Let us now consider how heat may be lost or gained by peculiarities of breathing. Taking, first, strictly normal conditions, we will suppose that the atmosphere is somewhat below the temperature of the body and below the saturation point. Respiration, under these conditions taking place slowly and gently, the maximum and minimum pressures do not deviate greatly from that of the atmosphere. Expiration takes place so slowly that we may suppose a considerable portion of the heat of compression to be given up to the circulation before the tidal air leaves the body. Practically no heat will be gained or lost from the tidal air. The aqueous vapor of the tidal air enters the body at the pressure and temperature of the atmosphere, leaving it at the temperature of the body and pressure p_1. A certain amount of water will therefore be evaporated in the lungs. The evaporation of this water and the warming of the tidal air will, therefore, absorb a moderate amount of heat which will play an important role in maintaining the equilibrium of the body.

Let us next consider the body placed (naked) in a very cold atmosphere. There will at first be a very rapid loss of heat at the surface, with the thermotaxic mechanism quickly checks by shutting off the peripheral circulation. But it is important that the moderate absorption of heat, which, we have seen above, takes place during ordinary breathing, should be reduced to a minimum. This can be done by compressing strongly the tidal air in the lungs by means of the chest muscles and holding it so compressed for quite a long period, after which it is suddenly expelled and the process repeated. By holding it compressed it will have time to give up all its heat of compression to the circulation, and besides the aqueous vapor in it will be reduced to a minimum, viz., the amount necessary to saturate its small mass at the temperature of the body and the high pressure p_1.

By such a means of breathing the heat usually absorbed by the lungs is reduced to a minimum and, if the difference of temperature of the body and atmosphere are not too great, there may be even a generation of heat in the lungs.

As a matter of fact, after a plunge into cold water, or between the sheets of a cold bed, precisely such a peculiar kind of respiration is observed as could have no other effect than that mentioned above. The breathing consists of a deep gasp which draws in the greatest amount of air possible and then, all means of exit being closed, it is firmly compressed and held so for a long interval, at the end of which the tidal air is explosively expelled and the process repeated. It is evident that from the exaggerated compression a high initial temperature is acquired and, from the prolonged contact with the pulmonary capallaries ample time is given the air to part with all its heat above the temperature of the blood, and to condense the greatest amount of moisture possible, by means of the high pressure. The tidal air is then, under these conditions, launched out of the body suddenly, no time being given for it to take up any heat either by evaporation or expansion.

Let us suppose now that the body be placed in a saturated atmosphere or water of a higher temperature than the body. Here no heat can be lost by evaporation by the skin, on the contrary heat is passing continually into the skin. The gain of heat is everywhere positive except in the lungs, and there heat enough must be absorbed to maintain the equilibrium. How shall the lungs work so as to effect this increased absorption of heat? First a deep inspiration so as to get a large amount of tidal air, but the most important part is the expiration. A sudden compression develops an instantaneous increase of temperature and with it an evaporation of water sufficient to saturate the air at the temperature and pressure. These two factors—temperature and pressure—to be sure, work in opposite directions, but the temperature is much the more important of the two. A large amount of water is momentarily evaporated, and this must be suddenly expelled, otherwise the air will have time to cool down and give back heat, first by condensation, second by conduction.

The writer has observed, under the conditions given, precisely this kind of respiration. Where a maximum effect is necessary, the respirations, each of this peculiar kind, are much increased in frequency. The case of the shaggy-haired dog has already been noted. The action of the heart is coincidently much increased in order to distribute rapidly the cold so gained by the lungs.

Recurring to our expressions for a and b above, we see that there must be a certain critical temperature for every warm-blooded animal beyond which it cannot maintain its existence in a saturated atmosphere.

That is to say, theoretically, at this point it will be able to keep its temperature normal, while for a slight excess there will be a steady accumulation of heat in the body, which will result in death by heat. Such death we know clinically takes place under three chief forms which may be merged into each other. First, death may be due to simple elevation of temperature. We know that the vital-chemical processes of the body can only take place within a very narrow range of temperatures, just as in the laboratory certain reactions require a definite temperature. When this temperature is increased the vital-chemical reactions in all the tissues are disturbed. The normal action of the brain cells is changed—coma results. The muscles also change their composition and their function of transforming the potential energy of various compounds into kinetic energy becomes deranged. Such a form of death takes place if the lungs and heart have been able to hold out thus long in the unequal contest. When one or the other succumbs to the excessive strain put upon it, we have death by respiratory or heart failure, which are familiar enough forms to practitioners who have seen many cases of sun stroke.

Let us suppose that we have a saturated atmosphere of 80°, and that the ratio $l=\frac{7}{11}$, perhaps an average value. Under these conditions we find that $a=.145$ and $b=.132$ $a > b$. Consequently heat will be gained with every breath and the individual could not long survive. 80° therefore is above the critical temperature for a human being where the tidal air is about half a litre and the ratio l cannot much exceed $\frac{7}{11}$.

If A is the quantity of heat that enters or leaves the surface of the body (according to sign), B is the heat generated by the heart, and C is the heat due to katabolism, all in the time of one respiration, we may write $A + B + C + m\, s_p\, (\theta - T) = (b - a)\, L_T$, * where L_T is the latent heat of water at temperature T. All these quantities except C are capable of direct measurement, and knowing the others, C can be found. When the body is at rest it is probable that this value is very small. For high temperatures also, certain experiments of the writer indicate that A is quite small. We may give then as an approximate value of the critical temperature of the human being 65° or 70° (about 155° Fahr.).

It would be eminently desirable if observations upon a warm-blooded animal could be carried out from a strictly thermo-dynamical point of view. Such experiments, requiring the conveniences of a laboratory, the writer has not had the opportunity of carrying out.

* A small term—the heat necessary to raise (b-a) grammes of vapour from T to t:—is here neglected.

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