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ON THE METABOLISM OF MATTER IN THE LIVING
BODY.

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A GREAT many so-called metabolism experiments have been made upon the human body and upon animals in which a balance of nitrogen or of nitrogen and carbon was obtained. That is, the quantity of nitrogen or of nitrogen and carbon in the food was determined by analyzing samples of the food, and the quantity of these elements in the excreta and the products of respiration was also determined. If the nitrogen taken into the body during the course of an experiment exceeds that given off from the body in the same period, then there is a net gain of nitrogen, and this is taken to indicate an increase in the total amount of protein of the body. Conversely, if the outgo of nitrogen exceeds the receipts there is a net loss, and this indicates a loss of protein. As protein contains 16 per cent. of nitrogen, the quantity of protein gained or lost is found by multiplying the gain or loss of nitrogen by 6.25. But protein also contains 53 per cent. of carbon. Hence, before striking a balance of the carbon, we must insert on one side or the other of the account, the quantity of carbon in the protein which has been gained or lost. The net gain or loss of carbon is then taken as a measure of the amount of fat which has been gained or lost from the body during the experiment. As fat contains 76.5 per cent. of carbon, the quantity of fat gained or lost is found by dividing the gain or loss of carbon by the factor .765.

These experiments in which both a nitrogen and carbon balance are determined require a determination, as has been said, not only of the nitrogen and carbon of the food and excreta, but also of the quantity of carbon dioxid given off from the lungs and skin; that is, of the products of respiration. They are hence called respiration experiments. Sometimes the subject of the experiment has worn a mask in such a manner as to respire air drawn from a particular source, the composition of which is determined, while the air expelled from the lungs is carried away to a reservoir, and its contents of oxygen and carbon dioxid subsequently determined. This gives the quantity of oxygen absorbed and of carbon dioxid exhaled. But such an experiment neglects the respiration of the skin, and is unsatisfactory on other accounts. The better method is to confine the subject in a chamber and to analyze samples of the air supplied to the chamber, and also other samples drawn from the current of air flowing away from the chamber.

In the experiment reported by Atwater and Rosa in the September and October numbers of the *PHYSICAL REVIEW*, as well as in subsequent experiments with the same apparatus, a nitrogen and carbon balance was obtained and also a balance of energy. For the latter, the potential energy of the food eaten by the subject was determined by burning samples in a calorimeter; the potential energy of the excreta was determined by burning samples of the dried residue in a similar manner; the heat given off from the body during the experiment was also measured, the respiration chamber being at the same time a calorimeter, hence called a respiration calorimeter. A balance of energy can then be reached by taking account of the quantity of protein and fat gained or lost. Such a balance of energy, to within about one or two per cent. has been obtained in a considerable number of experiments at Middletown, and the work is still being carried on.

A balance of hydrogen is more difficult to obtain than are the nitrogen and carbon balances. This involves, of course, the determination of the organic hydrogen of food and excreta, and also the quantity of water in the same and the quantity of water exhaled from the skin and lungs. The water vapor contained in the current of air entering the calorimetric chamber, and also that leaving through

the outgoing current of air are determined by absorption in sulphuric acid tubes at the same time that the carbon dioxide is absorbed by soda lime. But water being to some extent condensed upon the walls of the chamber, and absorbed by the clothing of the subject and the furnishings of the chamber, the exact determination of the water becomes a more difficult matter than that of the carbon dioxide, and a hydrogen balance has been seldom attempted.

It is impossible for one who has not been engaged in it to appreciate the difficulty and complexity of this kind of experimental work, or the enormous amount of labor and computation necessary to obtain the final results of a four days' respiration experiment. In the Middletown experiments analyses of samples of food were made in duplicate, and all determinations of carbon dioxide and water in the air current were in duplicate. But in spite of the greatest care residual errors are not inappreciable. And in weighing the food and drink, selecting samples for analysis, and in collecting and weighing the water condensed inside the chamber and outside in the freezers, errors of appreciable magnitude are bound to occur. Hence when one strikes a balance of nitrogen and carbon and computes the number of grams of protein and fat which have been gained or lost, the algebraic sum of a large number of errors appears in the result. Moreover, in an energy experiment this error is carried over into heat account in a magnified degree. Suppose, for example, that in the determination of the carbon of the food there is an error of one-half of one per cent.; the quantity of carbon in the daily ration being 261.5 g., this amounts to an error of 1.3 g., or 1.7 g. of fat. The heat value of a gram of fat being 9.4 large calories, 1.7 g. is equivalent to 16.0 calories, which is 0.7 per cent. of the total heat per day. An error in the nitrogen, however, produces a comparatively small error in the computed heat; for if the protein gained be reckoned too large, the fat gained will be too small in a corresponding degree, and the difference of heat value produced is relatively small.

In order to locate the sources of error and to reduce them in magnitude to a minimum, it is desirable to make use of every possible check upon the analyses and computations. Such a check may be found in the change of weight of the subject of the experi-

ment, provided the oxygen taken up from the air by respiration can be determined. Direct determinations of oxygen have been made in short experiments, by analyzing the air in the chamber at the beginning and at the end, and admitting to the chamber during the experiment a known quantity of oxygen. But for long experiments this is impracticable, as the air of the chamber must be frequently renewed. On the other hand, it is impossible to analyze the air by sample, as is done for CO_2 and H_2O , and determine the percentage of oxygen in the ingoing and outcoming air currents with sufficient accuracy. For if 50 liters of air be admitted to the chamber per minute, the quantity of oxygen in 24 hours will be about 20,000 g. and an error of one-tenth of one per cent. in the determination would amount to 20 grams, which would be an error of three per cent. in the amount of oxygen absorbed by the lungs.

On the other hand, an oxygen balance may be obtained in a manner similar to that followed for N, C and H. If the quantity of these latter elements and the ash of the food and excreta are accurately determined, then the amount of oxygen becomes known. The oxygen of the water of income and outgo is accurately known when the quantity of water is determined, and hence one can readily calculate the total amount of oxygen taken into the body and the total given out. The difference will represent that derived from the atmosphere by respiration. If it be objected that this determination of oxygen by difference is not sufficiently exact it may be replied, first, that if the oxygen is not exact then the other elements, N, C and H, are not exact; and, second, that the dry residue of food and excreta contains over 30 per cent. of oxygen, a greater proportion than that of any other constituent except carbon, and hence a determination by difference is far more reliable than where that difference is a small quantity, as, for example, in the case of the protein and fat gained or lost. But the latter quantities are regularly calculated by difference, with no check upon the results to show them to be correct. It is now proposed in a similar manner to calculate the hydrogen and oxygen by difference, and then to determine the oxygen taken up from the air in the manner of Pettenkofer and Voit,¹ from the gain or loss of weight of the

¹ The accuracy of weighing of these distinguished investigators was evidently not sufficient for the purpose.

subject, and to compare the two results thus derived by two independent methods. Or, having computed in the manner already indicated the amount of oxygen absorbed from the atmosphere, we are to calculate the gain or loss of weight of the person or animal which is the subject of the experiment. And if this weight is ascertained by an accurate balance at the beginning and end of the experiment, we have a means of checking by the difference the accuracy of the experiment. But if the subject is weighed four times each day, that is at the beginning of each six-hour period, and the observed weight tallies each time closely with the computed weight, we have a still better verification of the work. The probability is that considerable discrepancies would appear between the observed and computed weights, which would point out the more important sources of error, and thus serve as a means of increasing the accuracy of the work, besides sometimes detecting accidental errors of importance which would not otherwise be noticed.

It was such considerations as these that led to the purchase several years ago of an accurate scale, capable of weighing up to 100 kilos, which was put inside the calorimeter and the subject weighed himself several times during each experiment. However, this check was not applied, and the weighings, though made and recorded were never made use of. Having now retired completely from the investigation, I wish to present here the method which I devised about five years ago and to work it out for the experiment that was published in the recent numbers of the *PHYSICAL REVIEW*. The weighings were not as accurately nor as frequently made as they might have been; indeed, for this purpose they would better be made by the observers outside, and not by the subject within. I will indicate later how this can readily be done.

Table I, gives the balance of N,C,H,O and ash for the four days taken together. Under each element are two columns headed "In" and "Out," containing respectively the amounts of that element in the income of the body from all sources and the outgo of all kinds. These columns should balance, after the manner of the debit and credit columns of a ledger account, when one has inserted the balancing item. In the case of nitrogen this is the amount of nitrogen acquired from the protein of the tissues which was broken down

TABLE I.

Balance of Nitrogen, Carbon, Hydrogen and Oxygen.

Materials of Income and Outgo.	Total.	Nitrogen.		Carbon.		Hydrogen.		Water.		Oxygen.		Ash.	
		In.	Out.	In.	Out.	In.	Out.	In.	Out.	In.	Out.	In.	Out.
Food, Water.	Grams. 3684.0					412.0		3684.0		3272.0			
“ Solids.	2208.0	76.4		1046.2		150.4				845.8		89.2	
Water of Drink.	5382.0					602.0		5382.0		4780.0			
Oxygen from Air.	2611.6									2611.6			
Feces, Water.	308.8						34.5		308.8		274.3		
“ Solids.	115.2		5.0		53.4		7.3				30.5		19.0
Urine, Water.	6421.0						718.2		6421.0		5702.8		
“ Solids.	281.4		73.7		50.3		13.4				68.0		76.0
Water of Respiration.	3765.0						421.1		3765.0		3343.9		
Carb. Dioxide of Res.	3279.8				894.5						2385.3		
From Comb. of Body Protein.	14.4	2.3		7.6		1.0				3.5			
“ Storing of Body Fat.	72.7				55.6		8.7				8.4		
“ Dimin. of Body Water.	338.1					37.8		338.1		300.3			
“ Oxid. of Org. Hydro.	150.4+1.0												
of food, less that in feces,	-(7.3+13.4							1090.7					
Urine and Stored.	+8.7)=122.0											5.8	
		78.7	78.7	1053.8	1053.8	1203.2	1203.2	10494.8	10494.8	11813.2	11813.2	95.0	95.0

over and above what has been formed; for carbon, the amount contained in the fat stored away during the experiment; for hydrogen, the amount derived from the decrease of the water contained in the body; for oxygen, the amount derived from the atmosphere; and for ash, the loss of mineral matter of the body. These balancing items are printed in bold faced type.

The daily ration weighed 1,473 g., of which 921 g. was water and 552 g. dry solids. Thus in four days the water amounted to 3,684 g. and the dry solids to 2,208 g. These quantities are entered in the table in the column of totals. Taking the atomic weights of hydrogen and oxygen as 1 and 15.88, water contains 11.185% of hydrogen and 88.815% of oxygen. The water of the food, therefore, contains 412 g. of hydrogen and 3,272 g. of oxygen, and these items are entered in the proper columns under hydrogen and oxygen respectively. Analysis of samples showed that the dry residue contained 76.4 g. of nitrogen, 1,046.2 g. of carbon, 150.4 g. of hydrogen, and 89.2 g. of ash. The remainder, 845.8 g., is oxygen. All these items are entered in the table in their appropriate places. The 5,382 g. of water drunk (more than half of this was in coffee), in addition to that contained in the food, consisted of 602 g. of hydrogen and 4,780 g. of oxygen. The amount of water is also entered in the column of water. The fourth item of income, oxygen received from the air, is entered last of all, being a balancing item.

We get an approximate check upon the oxygen of the food in the following manner. The dry residue contained:

Protein,	478.4 g., of which 24.0% is oxygen =	114.8 g.
Fat,	276.0 " " 11.5% " =	31.6
Carbohydrates,	1364.4 " " 50.0% " =	682.2
Ash,	89.2 " "	0.
Total = 2208.0 g.		Total oxygen = 826.6 g.

As these percentage compositions are not exact we cannot regard this as more than a rough check upon the direct analyses, although the true value may perhaps lie between the two.

The next four lines in the table give the amounts of the various elements in the solid and liquid excreta, the total weights of which

are inserted in the column of totals, and the quantity of each element in the "out" column of that element. The water and carbon dioxid of respiration in like manner go into the column of output, the latter being exactly $\frac{8}{11}$ carbon and $\frac{8}{11}$ oxygen; that is, the atomic weight of carbon is 11.91 if oxygen is 15.88, or 12 if oxygen be taken at 16.

We now come to the balancing items:

First, the output of nitrogen is 2.3 g. more than the income. We therefore insert 2.3 as the balance, and this multiplied by 6.25 gives 14.4 g. as the weight of protein lost. This is entered in the column of totals and 7.6 g. of carbon, 1 g. of hydrogen and 3.5 g. of oxygen also contained in the protein are charged into the debit side of those accounts.

Second, the receipts of carbon exceed the output by 55.6 g. Hence we insert this as the balancing item and put 72.7 g. in the column of totals as the weight of the fat in which this carbon is stored up; 8.7 g. of hydrogen and 8.4 g. of oxygen are also contained in this fat, and these items are accordingly entered in their proper places.

Third, the output of hydrogen exceeds the receipts by 37.8 g. This is explained by the fact that the amount of water in the body must have decreased during the experiment by 338.1 g., for no other source of hydrogen remains to be considered. This is indeed the only way of ascertaining the change in the content of water in the body. The accuracy of this determination of course depends upon the accuracy of the several items occurring in the hydrogen columns. There is reason to believe they are less accurate than those of the nitrogen and carbon accounts, but the result of this computation is to give a check which tests the hydrogen account more than any other in the table.

Fourth, the item of 338.1 g. of water lost must be entered in the debit column of the water account, and 300.3 g. in the oxygen account. It represents the amount derived from the body's capital stock at the beginning of the experiment. To balance the water account we must take note of the fact that the organic hydrogen of the food when it is oxidized forms water, which must be charged into the debit side of the water account; or rather, the excess of hydrogen

contained in the food (150.4) and that contained in the protein used up (1.0), over that contained in the feces (7.3), urine (13.4) and that stored up in the fat accumulated (8.7). Thus: $150.4 + 1 - (7.3 + 13.4 + 8.7) = 122.0$ g. of hydrogen, which has been oxidized and formed 1090.7 g. of water. Entering this item on the debit side of the water account, the latter balances exactly.

Fifth, the oxygen account is now complete except the balancing item of 2611.6 g., which represents the quantity of oxygen derived from the atmosphere. This assumes that whatever quantity of oxygen is stored up as such or as oxyhaemoglobin in the blood and in the tissues does not vary by an appreciable amount; or, at least, that it was sensibly the same at 7 o'clock on the morning that the experiment began that it was at 7 o'clock on the last morning. This shows an absorption of 27.2 g. per hour or .45 g. per minute.

The balance of oxygen may be put in another form by omitting from both sides of the account the oxygen from the water which is received into the body. It then appears as follows:

BALANCE OF OXYGEN FOR FOUR DAYS.

	Receipts.	Output.
From the food	845.8	
From 14.4 g. protein of the body	3.5	
Excreted in feces (solids)		30.5
" urine "		68.0
" carbon dioxide		2385.3
" water from organic hydrogen		968.7
Stored away in fat		8.4
Balance from atmosphere	2611.6	
	<u>3460.9</u>	<u>3460.9</u>

Sixth, the column of ash does not balance as closely as it ought. There could not be a loss of 5.8 g. of mineral matter, and hence this difference must be mainly due to error in some one or more of the items given. Indeed, the record does not show positively whether all three items were actually determined. A change in any of them would alter the oxygen item by the same amount, but this would affect the final result only slightly, and for the present purpose it makes no difference.

We are now in position to calculate the loss of weight of the person under investigation, during the four days he was confined in the

respiration chamber. We must first note the fact that the feces passed during these four days weighed 498.4 g., being 74.4 g. more than those which belonged to that period, the latter being distinguished by the use of charcoal.

BALANCE OF MATTER.			
INCOME.		OUTGO.	
	Grams.		Grams.
Food	5892.0	Feces	498.4
Drink	5382.0	Urine	6702.4
Oxygen from air	2611.6	Water of respiration	3765.0
Balance = Loss of weight	360.0	Carbon dioxid of respiration . . .	3279.8
	<u>14245.6</u>		<u>14245.6</u>

This loss of 360 grams in weight is made up as follows :

Loss of water from body, see Table I., =	338.1 g.
“ “ feces “ “ “ “ “ “ =	74.4
“ “ protein “ “ “ “ “ “ =	14.4
“ “ ash “ “ “ “ “ “ =	5.8
	<u>432.7</u>
Gain of fat, “ “ “ “ “ “ =	72.7
Net loss of weight, as above,	<u>360.0</u>

Now the weight of the man at the beginning was 68,420 g. and at the end was 68,000¹ g., making a loss of 420 g., or 60 g. more than the calculated loss. This is of course not a very close agreement. The discrepancy may be partly accounted for by the fact the weighings of the subject by himself were not as exact as if made by some one else, and were not made at the exact time of beginning and end. The computed loss of weight is of course in error by an appreciable amount, but for want of more reliable weighings we cannot say definitely what the error is.

Tables II. and III. give the results of a similar computation for each day separately. The food was the same each day, although there was a slight variation of the water of the food and on the first day the water of the drink was about 200 g. more than on the subsequent days. The feces, although passed in only two portions, were assumed to be separated in equal quantity each day. There was only a slight variation from day to day in the evolution of

¹ The record of this weight is 67,200, but from a previous weight it is evident that this is an error and should be 68,000.

Balance of Nitrogen, Carbon and Hydrogen.—By Days.

Materials of Metabolism.	Carbon.							
	1st Day.		2d Day.		3d Day.		4th Day.	
Food, Water.	Income.	261.5		261.5		261.6		261.6
" Solids.								
Water of Drink.								
Oxygen from Air.	Outgo.							
Feces, Water.								
" Solids.								
Urine, Water.								
" Solids.								
Water of Respiration.								
Carb. Dioxide of Res.								
From Comb. of Body Protein.	3.0		3.0		1.3		0.3	
" Storing of Body Fat.	11.7		16.6		1.3		11.0	
" Dimin. of Body Water.								
" Oxid. of Org. Hydro. of food, less that in feces, Urine and Stored.								
Loss of Ash.								
	264.5	264.5	264.5	264.5	262.9	262.9	261.9	261.9
Fat Stored :	1.52		21.7		21.4		14.4	
	Total = 72.7							

TABLE II.—*Continued.*

Materials of Metabolism.	Hydrogen.							
	1st Day.		2d Day.		3d Day.		4th Day.	
Food, Water.	103.0		102.8		103.0		103.2	
“ Solids.	37.6		37.6		37.6		37.6	
Water of Drink.	167.0		144.3		145.4		145.3	
Oxygen from Air.								
Feces, Water.		8.6		8.6		8.7		8.6
“ Solids.		1.9		1.8		1.8		1.8
Urine, Water.		199.5		213.1		161.3		144.3
“ Solids.		3.4		3.4		3.3		3.3
Water of Respiration.		107.1		99.7		101.3		113.0
Carb. Dioxide of Res.								
From Comb. of Body Protein.	0.4		0.4		0.2		0.0	
“ Storing of Body Fat.		1.8		2.6		2.6		1.7
“ Dimin. of Body Water.	14.3		44.1		7.2		13.4	
“ Oxid. of Org. Hydro.								
of food, less that in feces,								
Urine and Stored.								
Loss of Ash.								
	322.3	322.3	329.2	329.2	286.2	286.2	286.1	286.1

TABLE III.

Balance of Water, Oxygen and Ash.—By Days.

Materials of Metabolism.	Water.							
	1st Day.		2d Day.		3d Day.		4th Day.	
Food, Water.	921.0		919.0		921.0		923.0	
“ Solids.								
Water of Drink.	1492.8		1289.9		1299.5		1299.8	
Oxygen from Air.								
Feces, Water.		77.2		77.2		77.2		77.2
“ Solids.								
Urine, Water.		1783.6		1906.0		1440.9		1290.5
“ Solids.								
Water of Respiration.		957.9		891.7		905.9		1009.5
Carb. Dioxide of Res.								
From Comb. of Body Pro.								
“ Storing of Body Fat.								
“ Dim. of Body Water.	127.8		396.0		65.6		120.1	
“ Ox. of Or. Hydro.								
of food, less that in								
feces, Ur. and Stored.	277.1		270.0		269.1		274.5	
Loss of Ash.								
	2818.7	2818.7	2874.9	2874.9	2489.6	2489.6	2497.3	2497.

TABLE III.—*Continued.*

Materials of Metabolism.	Oxygen.							
	1st Day.		2d Day.		3d Day.		4th Day.	
Food, Water.	818.0		816.2		818.0		819.8	
“ Solids.	211.5		211.5		211.4		211.4	
Water of Drink.	1325.8		1145.6		1154.1		1154.5	
Oxygen from Air.	664.3		645.9		642.6		658.8	
Feces, Water.		68.6		68.6		68.6		68.5
“ Solids.		7.6		7.6		7.6		7.7
Urine, Water.		1584.1		1692.9		1279.6		1146.2
“ Solids.		17.3		17.3		16.8		16.6
Water of Respiration.		850.8		792.0		804.6		896.5
Carb. Dioxide of Res.		604.4		591.6		588.6		600.7
From Com. of Body Pro.	1.4		1.4		0.6		0.1	
“ Storing of Body Fat.		1.7		2.5		2.5		1.7
“ Dim. of Body Water.	113.5		351.9			58.4		106.7
“ Ox. of Or. Hydro. of food, less that in feces, Ur. and Stored.								
Loss of Ash.								
	3134.5	3134.5	3172.5	3172.5	2826.7	2826.7	2844.6	2844.6

Materials of Metabolism.	Ash.							
	1st Day.		2d Day.		3d Day.		4th Day.	
Food, Water.								
“ Solids.	22.3		22.3		22.3		22.3	
Water of Drink.								
Oxygen from Air.								
Feces, Water.								
“ Solids.		4.8		4.8		4.7		4.7
Urine, Water.								
“ Solids.		19.4		19.4		18.8		18.4
Water of Respiration.								
Carb. Dioxide of Res.								
From Comb. of Body Pro.								
“ Storing of Body Fat.								
“ Dim. of Body Water.								
“ Ox. of Or. Hydro. of food, less that in feces, Ur. and Stored.								
Loss of Ash.	1.9		1.9		1.2		0.8	
	24.1	24.1	24.1	24.1	23.6	23.6	23.2	23.2

carbon dioxid, but a greater difference in the water of respiration and a still greater variation in the urine. The quantity of the latter was so great the first two days that the total amount of water in the body decreased 523.8 g., but during the last two days it increased 185.7 g. The quantity of oxygen derived from the air varies but little, and in nearly the same degree as the evolution of carbon dioxid. The quantity of both oxygen and carbon dioxid was greater on the first and fourth days than on the two intervening days. The ratio of the carbon dioxid exhaled to the oxygen absorbed, called the respiratory quotient, is so important that I have put down the value for each day.

	1st Day.	2d Day.	3d Day.	4th Day.	Total.
Carbon dioxid exhaled,	831.1	813.4	809.3	826.0	3279.9
Oxygen absorbed,	664.3	645.9	642.6	658.8	2611.6
Respiratory quotient,	1.251	1.259	1.259	1.254	Ave., 1.256

The respiratory quotient for the first day is 0.4% less than the average, corresponding to 2.6 g. of oxygen: that of the second and third days is 0.2% more, corresponding to 1.6 g. of oxygen, while that of the fourth day differs still less, corresponding to only 1.1 g. of oxygen. We know that the respiratory quotient should not be exactly constant from day to day in this experiment, because the receipts and expenditures of oxygen aside from respiration varied slightly. But these variations were only slight, and the nearly constant value of the respiratory quotient is an evidence of the correctness of the values of the oxygen absorbed from the atmosphere, as calculated in the table.

Table IV. gives the balance of matter for each day of the experiment and the calculated gain or loss each day. For the first day there is a discrepancy of 145.4 g. This indicates either a serious error in weighing or else a large error in the water account of that day. For the second day the difference is — 42.6 g., the third day practically nothing, the fourth day — 42.1 g., the total for the four days being 60 g. If the weighings had been more accurate and at exactly 7 o'clock each morning, the result would be more conclusive. But the present purpose is to show how this check may be made in future, rather than to seek to confer any benefits upon past experiments.

TABLE IV.
Balance of Matter.

		1st Day.	2d Day.	3d Day.	4th Day.
Income.	Food, Water.	921.0	919.0	921.0	923.0
	“ Solids.	552.0	552.0	552.0	552.0
	Drink, Water.	1492.8	1289.9	1299.5	1299.8
	Oxygen of Air.	664.3	645.9	642.6	658.8
Outgo.	Feces.	—	216.6	—	281.8
	Urine.	1855.3	1977.6	1510.6	1358.9
	Water of Respiration.	957.9	891.7	905.9	1009.5
	CO ₂ of Respiration.	831.1	813.4	809.3	826.0
	Balance.	14.2	492.5	189.3	42.6
		3644.3-3644.3	3899.3-3899.3	3415.1-3415.1	3476.2-3476.2
By Scales.		Lost 160.0	Lost 450.0	Gained 190.0	Lost 0.0
By calculation above.		“ 14.6	“ 492.6	“ 189.3	“ 42.1
Difference.		+145.4	-42.6	-0.7	-42.1

Difference for four days 60 grams, lost more by scales than by calculation.

But one can also calculate the weight of the subject at other times of the day and additional checks may thus be instituted which might be of service in locating errors and deriving the largest possible amount of information from an experiment. Suppose that it is desired to calculate the weight of the subject at the beginning of each 6-hour period, that is at 7 A. M., 1 P. M., 7 P. M. and 1 A. M. of each day. The CO₂ and H₂O of respiration are separately determined for each such period any way, and it is only a matter of slight computation to get all the data for a check upon the work four times each day, having the weight of the subject by an accurate scale at the same times.

In computing the fat gained or lost from the gain or loss of carbon, it is assumed that the glycogen and other carbohydrates of the body at 7 A. M. each day are constant in quantity, the diet being uniform from day to day. In order that the same assumption might hold true, or approximately so, for the six-hour periods it would be desirable to serve the meals just after the beginning of the periods. Then the glycogen content of the liver and tissues would be more nearly uniform than if supper were served at 6:30, as was done in these experiments. Even then, of course, it would vary,

but the error introduced by the probable variation would not be considerable.

TABLE V.
Table of Gain and Loss.

	1st Day.		2d Day.		3d Day.		4th Day	
	Gain.	Loss.	Gain.	Loss.	Gain.	Loss.	Gain.	Loss.
Water.		127.8		396.0	65.6		120.1	
Feces.	106.0			110.6	106.0			175.8
Protein.		5.7		5.7		2.5		0.5
Fat.	15.2		21.7		21.4		14.4	
Ash.		1.9		1.9		1.2		0.8
Balance.	14.2		492.5			189.3	42.6	
	135.4	135.4	514.2	514.2	193.0	193.0	177.1	177.1

In the accompanying figures a graphic representation of the change of weight of the person during the 96 hours of the experiment is given. The points representing the weights at the end of every 6 hour period are inclosed in small circles, and the weight as computed is given in figures. Between these points the values are not exact, for it has been assumed that the evolution of H_2O and CO_2 and the absorption of oxygen were uniform during each period. Of course these quantities are greater during the exercise incident to dressing and eating than during subsequent rest, but for the purpose of illustrating the fluctuation of weight during a day, or during four successive days, this variation may be neglected. It would be of very great interest if we had the precise weight of the subject at each of these 17 six hour stations. Another source of uncertainty in the calculated weights at the six hour stations is that the respiratory quotient, determined above for each day separately, was assumed to be constant for the different periods of each day. But in experiments carried out with that in view it might be separately computed for each period. That might give information of value in itself as showing to what extent oxygen may be stored up in the body.

The chart is mainly self-explanatory. Starting at 7 o'clock on the morning of the first day with a weight of 68,420 g. the subject loses 45 g. in one hour by respiration. That is, the loss of CO_2

and H_2O above the gain of oxygen by respiration is 45 g. per hour during the first 6 hours. Breakfast adds 675 g. to his weight.

Fig. 1.

Fig. 2.

Of course the gain of weight due to breakfast was not instantaneous, but it was not deemed necessary or desirable to indicate the time occupied in eating meals by a sloping line. During the next $2\frac{1}{2}$

hours until 10:30 a loss of 110 g. occurred by respiration, and then a drink of water increased the weight by 200 g. A further loss of 110.3 g. by respiration was followed by a decrease due to passage of urine, and at one o'clock the weight should have been 68,689 g. We have no observed weight to compare with it, but the weights we have at seven o'clock each morning are plotted in the chart as stars.

The charts show very clearly the considerable fluctuations of weight throughout a period of 24 hours. The minimum weight is at eight o'clock, just before breakfast, and the maximum just after supper. The slope of the lines showing the loss of weight by respiration is nearly uniform, as the loss of weight is nearly as rapid at night during sleep as during the day. The evolution of CO_2 is only slightly more than half as much at night as during the day (and in a work experiment only about one-fourth) but the absorption of oxygen is also less in (nearly) the same ratio. On the other hand, the rate at which water is given off from the skin and lungs is nearly as great at night as in the day in a rest experiment (although far less at night than during the day when at work). Hence while there was a loss of 265 g. by respiration in 6 hours, from 7 a. m. to 1 p. m. on the first day, there was a loss of 254 g. from 1 a. m. to 7 a. m. during sleep.

While the check that is thus afforded by knowing the weight of the subject at intervals during the experiment would not detect small errors in the determination of nitrogen and carbon, it would detect appreciable errors in the determination of the water, and this is the quantity most in need of such a check. Considering the great labor and cost of complete respiration experiments it appears of the greatest importance to use every possible means to reduce errors to a minimum and to derive the maximum amount of information from each experiment.

In order to weigh the subject with the greatest possible accuracy, he should be seated quietly on the platform of the balance, and the weighing done from without. This may be accomplished by using a rider, controlling it by a rod from outside, in a manner similar to that in a chemical balance. The subject would set the heavy weight at such a point that the beam nearly balanced. The exact balance would then be secured by the rider. The beam should be visible

from without through the window, so that readings of the weight and rider could be made by the observer outside. The subject ought, however, to note and report the reading, when the weighing is finished, as a check upon the record of the observer. The position of exact balance could be obtained by use of a reading telescope, set in the walls of the chamber and a graduated scale attached to the beam would swing to and fro in the field. By observing the range, very close settings could be made, and with a good Fairbanks balance readings could be made at least to a single gram.

In order that these close readings be as reliable as possible, several successive weighings should be made. The subject is constantly growing lighter by the losses due to respiration. Hence the rider could be set a little to one side of a balance, and the time noted when exact balance was secured. A second setting would give a balance, say about a minute later. Let five such weights be made, extending before and after the time at which the weight is desired, and from the mean the true weight could be obtained to within a gram at least, not counting any constant error due to inaccuracy of the balance, which would be of no moment in taking the difference.

The subject should have a light suit of clothes, without pockets, and be weighed with his clothes on. Any moisture contained in his clothing would then be reckoned as part of himself. In a rest experiment this would be small, and the disturbance due to the exercise of dressing and undressing would be avoided.

MECHANICAL WORK.

The bicycle-dynamo combination, which we employed to develop and measure mechanical energy at the expense of the potential energy of food and tissue was not the ideal form of ergometer. It was easily arranged and served our purpose for the time being. But it required calibration and the energy expended in friction was somewhat variable ; moreover, it is probably not a machine in which the maximum efficiency of conversion could be effected. A better arrangement would be a simple treadmill. That is, a movable inclined plane consisting of slats attached to two endless chains, the latter running over sprocket pulleys. A fly wheel to steady the motion might consist of a heavy copper disc revolving between the

poles of permanent magnets, thus serving also as a brake. By varying the position of the magnets the braking effect and, therefore, also the rapidity of motion could be varied, and by varying the inclination of the plane greater or less force would be exerted. The three quantities required in order to calculate the work done in any given time would be (1) the angle of elevation of the plane, (2) the whole number of revolutions of the flywheel or sprocket pulley and the distance traveled by the plane for each such revolution, and (3) the weight of the person operating the mill. The first is easily determined by reading a graduated sector, the base being level; the second would be recorded by a simple counter; the third should be frequently determined for purposes of a check upon the observations and analyses, and hence would not involve any additional labor. This form of ergometer would enable a large or small amount of work to be done, would give a high efficiency of conversion, would require no calibration, would involve no error due to varying friction, would require no record of varying speed to be made, and could be constructed at a reasonable cost. With it a large variety of experiments could be made.

The conversion of the energy of food and tissue into mechanical energy is a profound mystery. We cannot understand how a contracting muscle transfers the energy liberated by the oxidation of matter into an outside portion of matter. Perhaps the heat produced by the oxidation is transformed by some process equivalent to that of a heat engine. If the second law of thermodynamics does govern the process, it may be that the requisite difference of temperature occurs only in spaces of the order of magnitude of molecules, and hence cannot be measured experimentally. Or it may be that the oxidation is accompanied by an evolution of less heat when work is done, as is the case when zinc is consumed in a battery furnishing a current of electricity. In other words, that it is in some way electrical, and hence that no such difference of temperature exists as would be required in a heat engine or its equivalent. Some such theory has been put forward, although it is far from explaining the process. It is possible that further experiments such as can be carried on with the respiration calorimeter will give such additional information as at least to assist in formulating a more satisfactory theory of the process.

But there is another case of interest which demands experimental examination. That is the converse case where work is done upon a man, for example, by an outside agent. If a laborer spends a day in hoisting brick to the top of a building by means of a windlass, the heat which his body gives out plus the work done upon the brick will equal the net potential energy of food and body tissue used up in the same time. Now suppose that next day he lowers the same brick to the ground again. The work done is negative in the mechanical sense, although the force exerted in handling the windlass is nearly as great as in hauling them up. Will the heat evolved *minus* the loss of potential energy of the brick equal the potential energy of food and body tissue used up? And will the heat yielded by the body be more or less than on the preceding day?

Or, again, suppose the windlass is driven by an engine while the laborer grasping the handle holds back with all his might. The engine does a large amount of work upon the man. What is the form that this energy assumes? Is oxidation checked by the exertion of force upon muscle?

Or, again, suppose a man is walking down hill. If he weighs 150 pounds and walks 10 miles down a grade of $14\frac{1}{2}^{\circ}$ he will descend vertically $2\frac{1}{2}$ miles and the potential energy given up by his body as a whole will be 1,980,000 foot pounds, which is equivalent to a horse-power working for an hour. What form does this energy take? Such an experiment could be performed in a respiration calorimeter by using the proposed treadmill for an inclined plane, and driving it by an electric motor, having the man walk down hill as the plane was driven up. Perhaps such experiments have already been made, but so far as I am aware no satisfactory answers to these questions have been reached.

An intermediate case is where force is exerted without doing work, as when a weight is held in the hands without being raised or lowered.

The suggestion that there is an energy-bearing product of mental effort which is capable of being apprehended by physical instruments is contrary to our physical notions. The increased generation of heat in the brain and head, due to increased circulation of

the blood or increased oxidation of tissue or other oxidizable material during mental activity is however something that can be studied. But it would require special apparatus other than, or in addition to, the respiration calorimeter.

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