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GROWTH AND DEVELOPMENT

With Special Reference to Domestic Animals

LIII. Resting Energy Metabolism and Ventilation Rate in Relation to Body Weight In Growing Jersey Cattle, with a Com- parison to Basal Energy Metabo- lism in Growing Man

SAMUEL BRODY, H. H. KIBLER, AND A. C. RAGSDALE

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FOREWORD

The special investigation on growth and development is a cooperative enterprise in which the departments of Animal Husbandry, Dairy Husbandry, Agricultural Chemistry, and Poultry Husbandry have each contributed a substantial part. The parts for the investigation in the beginning were inaugurated by a committee including A. C. Ragsdale, E. A. Trowbridge, H. L. Kempster, A. G. Hogan, and F. B. Mumford. Samuel Brody served as Chairman of this committee and has been chiefly responsible for the execution of the plans, interpretation of results and the preparation of the publications resulting from this enterprise.

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ABSTRACT

This bulletin presents charts, prediction tables in various units, and the fitted equation $Y = aX^b$ relating resting-maintenance energy cost, \bar{Y} , to body weight, X , for the same 18 Jersey cattle from birth to 25 months of age. These results are compared to a similar analysis of energy metabolism (mostly "basal metabolism") in humans from birth on. The value of the exponent b in the above equation is near unity from birth to 5 months in cattle and birth to 3 years in children; and near 0.6, from 6 to 25 months in cattle and 3 to 16 years in children. The metabolism per unit surface area rises from birth to about 6 months in cattle and from birth to about 3 years in humans; it remains roughly constant 6 to 25 months in cattle and declines somewhat 3 to 16 years in humans. Similar data are presented for the relation of ventilation rate to body weight in cattle. The value of b in the above equation for ventilation rate in cattle is about 0.72, birth to 25 months. Oxygen decrement in the ventilated air declines with increasing body weight; that is, more oxygen is taken out from a given volume of inspired air in the smaller animals. The implications, practical and theoretical, to students of nutrition and of ventilation and air-conditioning engineering, are discussed.

I. THE PROBLEM

One of the intriguing observations in animal nutrition is that the resting maintenance cost, or the so-called basal metabolism, of mature animals of different size, does not vary with simple body weight but with a fractional power of body weight. Thus the basal metabolism of a 100-pound mature animal is not 10-fold but about 7-fold that of a 10-pound mature animal¹. Many theories have been advanced² in explanation of this relation between resting metabolism and body weight in approximately mature animals of the same and of different species.

This report is concerned not with *mature* animals differing in size¹, but with the same *growing* animals. How does age and

¹Missouri Agric. Exp. Sta. Res. Bul. 220.

²Id., Res. Bul. 328.

growth rate influence the resting maintenance cost?

In addition to data on resting maintenance cost of growing animals, basic for a science of animal nutrition and of considerable interest to the animal feeder, this bulletin also presents data for ventilation rate (air volume inhaled per unit time), oxygen consumption, and, inferentially, carbon dioxide production and water-vapor exhalation, which are basic for ventilating and air-conditioning engineering.

To broaden the generality of the conclusions based on our cattle-metabolism data, a similar analysis is presented of human-metabolism data from the literature, and the results of the two analyses are compared critically.

II. DATA. METHODS

The data on oxygen consumption and ventilation rates were obtained on 18 Jersey heifers in our Station herd. The animals were measured before the morning feeding, from the earliest age until age 25 months. The feeding, care, and management were the same as for the heifers in the herd. They were possibly more gentle and more quiet, because they were well trained for the measurements and more used to being handled.

The method of measuring the metabolism was previously described¹ in detail and is illustrated in Fig. 1. The rate of oxygen consumption is measured directly by the rate of decline of the oxygen bell, recorded automatically on a clock kymograph.

The ventilation rate, that is the inhaled and exhaled air volume per minute, is computed from the amplitudes of the up-and-down movements of the oxygen bell corresponding to the inspiratory and expiratory movements of the lungs as recorded on the clock kymograph.

As the animals were measured before the morning feeding, 8 to 12 hours after the preceding evening feeding, they were not in post-absorptive condition since, unlike humans, cattle do not reach post-absorptive condition in 12 hours, but in about 48 hours (more or less depending on age and other factors). The oxygen-consumption data thus represent not "basal metabolism" but normal, early-morning, metabolism at rest in lying position. The data thus represent the approximately minimum maintenance-cost. Table 1 presents the minimum maintenance cost in terms of different units, computed from the equations in the text.

¹Missouri Agric. Exp. Sta. Res. Bul. 143, pp. 6 to 15.

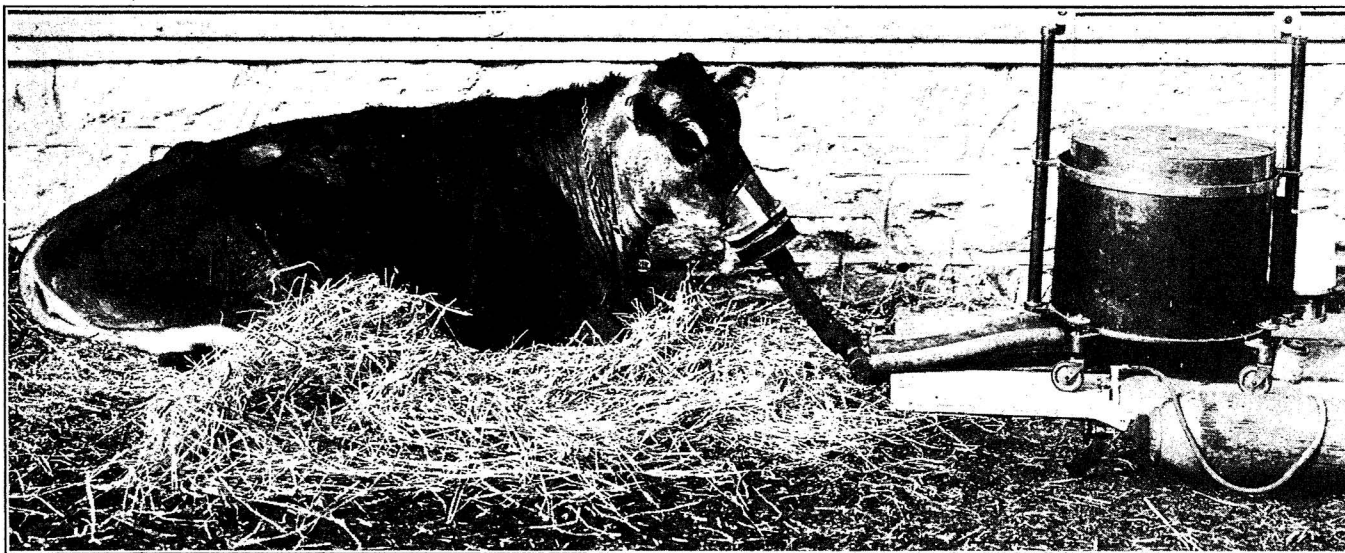


Fig. 1. Method of measuring oxygen consumption and ventilation rate.

TABLE 1. PREDICTION TABLE FOR RESTING ENERGY MAINTENANCE COST AND VENTILATION RATE IN GROWING JERSEY CATTLE.

Body Weight Kgs. Lbs.		Energy Maintenance Cost per 24 hours							Oxygen Consumption Per 24 hours (S.T.P.)			Ventilation Rate Per Minute (S.T.P.)				Ratio of oxygen consumption to ventilation rate	
		Calories			B.T.U.		Equi- ²	Feed ³	Liters		Cu. ft.		Liters		Cu. ft.		% O ₂ Liters consumed Air, Liters inhaled
		Total	Kg.	Per Sq. M. ¹	Total	Per Lb.	TDN lb.	Used TDN Lbs.	Total	Per Kg.	Total	Per Lb.	Total	Per Kg.	Total	Per Lb.	
25	55.1	1303	52.1	1420	5169	94	.7	---	270	10.8	9.5	.172	10.0	.402	.36	.0064	1.88
50	110.2	2364	47.3	1770	9381	85	1.3	1.9	490	9.8	17.3	.157	16.6	.331	.59	.0053	2.05
75	165.3	3329	44.4	1970	13210	80	1.8	3.0	690	9.2	24.4	.148	22.2	.296	.78	.0047	2.16
100 ⁴	220.5	3908	39.1	2050	15510	70	2.2	4.1	810	8.0	28.6	.130	27.3	.273	.96	.0044	2.06
125	275.6	4439	35.5	2050	17610	64	2.4	4.8	920	7.4	32.5	.118	32.0	.256	1.13	.0041	2.00
150	330.7	4922	32.8	2010	19530	59	2.7	5.2	1020	6.8	36.0	.109	36.5	.243	1.29	.0039	1.94
175	385.8	5356	30.7	1970	21250	55	3.0	5.5	1110	6.3	39.2	.102	40.8	.233	1.44	.0037	1.89
200	440.9	5790	29.0	1990	22970	52	3.2	6.2	1200	6.0	42.4	.096	44.9	.225	1.59	.0036	1.86
250	551.1	6562	26.2	2020	26040	47	3.6	7.3	1360	5.4	48.0	.087	52.7	.211	1.86	.0034	1.79
300	661.4	7238	24.1	2010	28710	43	4.0	8.8	1500	5.0	53.0	.080	60.1	.200	2.12	.0032	1.73
350	771.6	7913	22.6	1960	31400	41	4.4	9.6	1640	4.7	57.9	.075	67.2	.192	2.37	.0031	1.69
400	881.8	8492	21.2	1940	33670	38	4.7	---	1760	4.4	62.2	.071	74.0	.185	2.61	.0030	1.65
450 ⁵	992.1	9071	20.2	---	35990	36	5.0	---	1880	4.2	66.4	.067	80.5	.179	2.84	.0029	1.62
500 ⁵	1102.0	9650	19.3	---	38290	35	5.3	---	2000	4.0	70.6	.064	86.9	.174	3.07	.0028	1.60

¹Calories per square meter were read from Fig. 5. Surface area was computed from the equation, surface area in sq. meters = 0.15 (weight in kg.)^{0.56}. See Mo. Res. Bul. 89, p. 10. The heat production was computed on the assumption that one liter of oxygen has a heat equivalent of 4,825 Calories. This value is probably slightly high for the younger calves taking milk and low for the older heifers. The error incurred by this assumption is well within the experimental error.

²Computed on the assumption that 1 lb. TDN (total digestible nutrients) is equivalent to 1814 Cal. or 1 gm. of TDN to 4 Cal.

³Interpolated from page 10 of Mo. Exp. Sta. Bul. 338 covering feed records for large groups (36 to 63 animals).

⁴Computations for body weights of 100 Kg. and larger are based on equation (2), Fig. 2, and those for smaller body weights on equation (1), Fig. 2.

⁵Computations for these body weights are extrapolations beyond the range of actual data.

The shape and slope of the curve relating metabolism to body weight varies from animal to animal depending on the date of birth and the associated seasonal factors affecting growth and metabolism. Differences in intestinal "fill" with the associated heat increment of feeding (while the animals were regularly fed the preceding evening, they usually also had access to some hay or pasture at night) also contributed to the variability of the data. In brief, the data represent oxygen consumption not of laboratory animals living under a calorimeter-chamber regime, but of animals living and cared for under typical commercial dairy herd practice and measured under conditions representative of normal rest in a commercial dairy barn in the early morning, before the morning feeding.

III. GENERALIZATIONS

Large bodies of numerical data are not necessarily useful and often confusing, unless welded together into a simple generalization, a so-called "law" in the form of an equation, which may be used for practical prediction purposes.

1. Relation of metabolism and of ventilation rate to body weight in growing Jersey cattle.—The simplest and best-known generalization, which we previously used for relating metabo-

lism to body weight in *mature* animals of *different species*, is the relative-growth or logarithmic equation

$$Y = aX^b \quad (1)$$

in which Y is metabolism for body weight. We also employ this equation in this bulletin to relate oxygen consumption, heat production, and ventilation rate to body weight in the *same growing* cattle.

The results of fitting equation (1), by the method of least squares, to the oxygen consumption data (for the 18 animals listed in Table 2) are shown in Fig. 2, and to the ventilation-rate data, in Fig. 3.

Table 2. JERSEY HEIFERS INCLUDED IN FIG. II

Herd no.	Metabolism-Measurement Period ¹ Month	Age Bred Months	Birth Month
818	3 wk. to 23rd	16	Sept.
819	Birth to 25th	17½	Nov.
820	3rd to 22nd	Free Martin	Nov.
821	1 wk. to 25th	19	Jan.
822	Birth to 25th	18	April
823	Birth to 25th	19	June
824	Birth to 9th	16	June
825	3rd to 22nd	16	July
826	2nd to 23rd	17	July
827	Birth to 25th	20	Nov.
828	Birth to 23rd	23	Nov.
829	1 wk. to 25th	20	Dec.
831	Birth to 25th	22	Feb.
833	Birth to 25th	18½	Feb.
834	Birth to 25th	19	March
835	Birth to 25th	20	April
836	Birth to 25th	19	April
837	6th to 25th	24	April

¹Periods included in general oxygen-consumption chart, Fig. 2, and Ventilation chart, Fig. 3.

Let us discuss Fig. 2, relating resting metabolism of the cattle to body weight. The light continuous line, labelled III, represents the relative-growth equation $Y = aX^b$ fitted to *all* the data by the method of least squares. The fit is not satisfactory. The early metabolism values sag considerably below the fitted line, while in the center of the chart, 60 to 150 kg. body weight, the fitted line sags below the metabolism data. The slope of the fitted curve, or its exponent b, is 0.63, meaning that

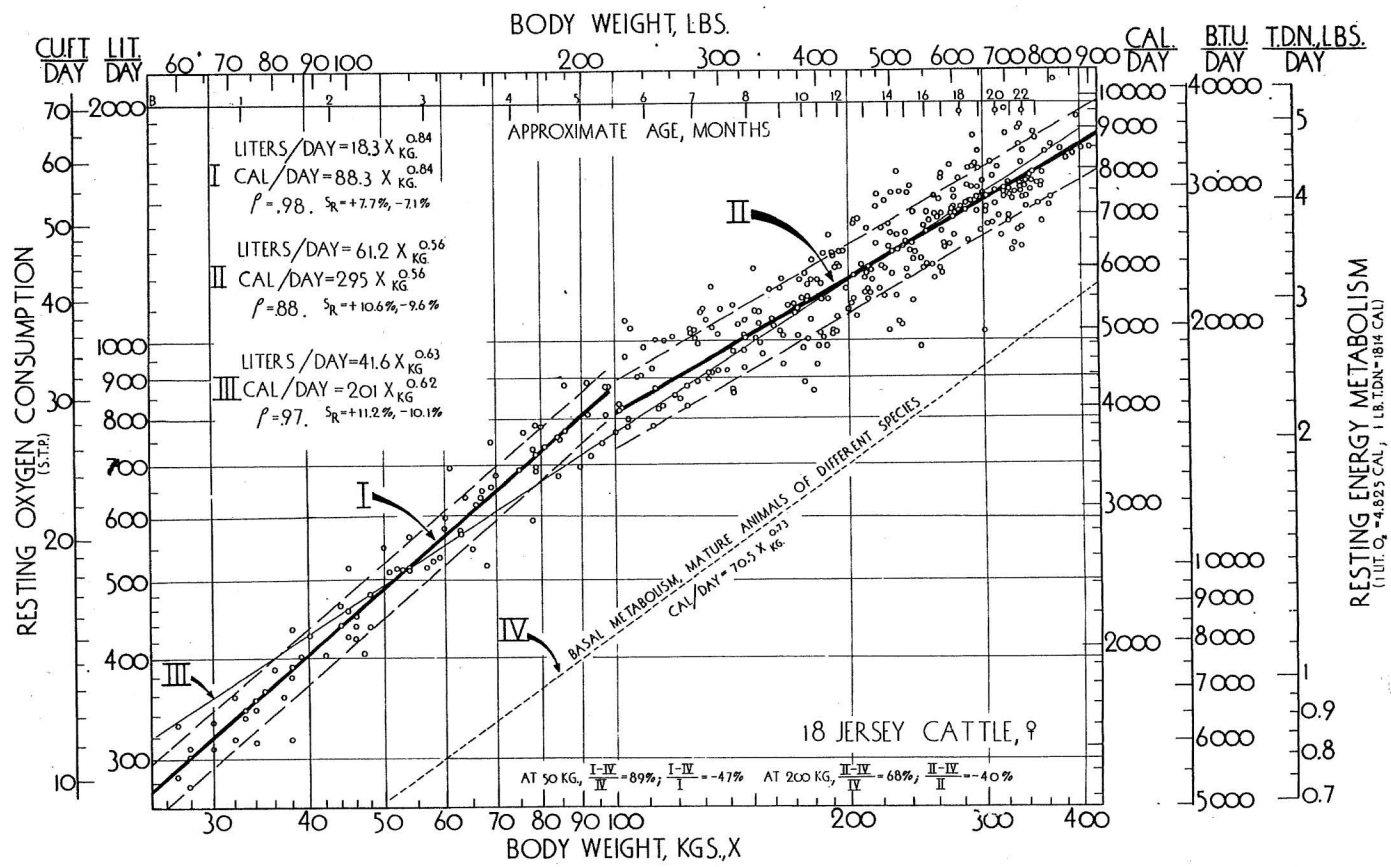


Fig. 2. Resting oxygen consumption (left axis) and heat production in terms of Cal., Btu, and TDN (right axis), plotted against body weight. The heavy line represents the equation $Y = aX^b$ with the values of a and b given on the chart, as well as of $\pm S_r$, which include $\frac{2}{3}$ of the data. The lowest dash line—40% below the heavy line—represents the equation $Y = 70.5X^{.73}$ for basal metabolism (Cal./day vs. body weight in Kg.) of mature animals of different species.

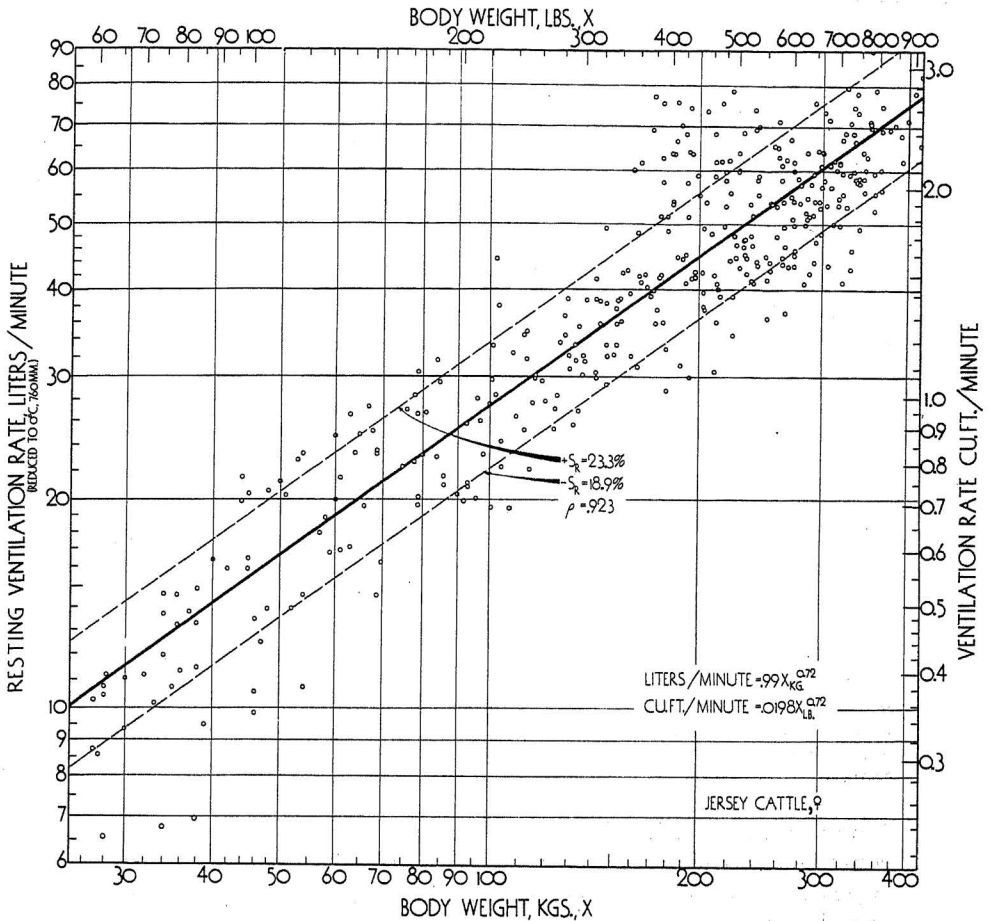


Fig. 3. Ventilation rate (volume of air expired or inspired per minute) plotted against body weight. As in Fig. 2, the heavy line represents the fitted equation $Y = aX^b$, the dash lines, the standard error of estimate.

increasing body weight 100% increases resting metabolism (resting maintenance cost) about 63%.

Let us next turn to Fig. 4, showing the same resting metabolism *per square meter surface area* plotted against age. The surface area in dairy cattle was found to be related to body weight by the relative-growth equation

$$\text{Surface area, sq. meters} = 0.15 \text{ weight}_{\text{Kg.}}^{0.56}$$

Fig. 4 shows that the resting metabolism per square meter rises from birth (about 1300 Cal./Sq. meter) to approximately

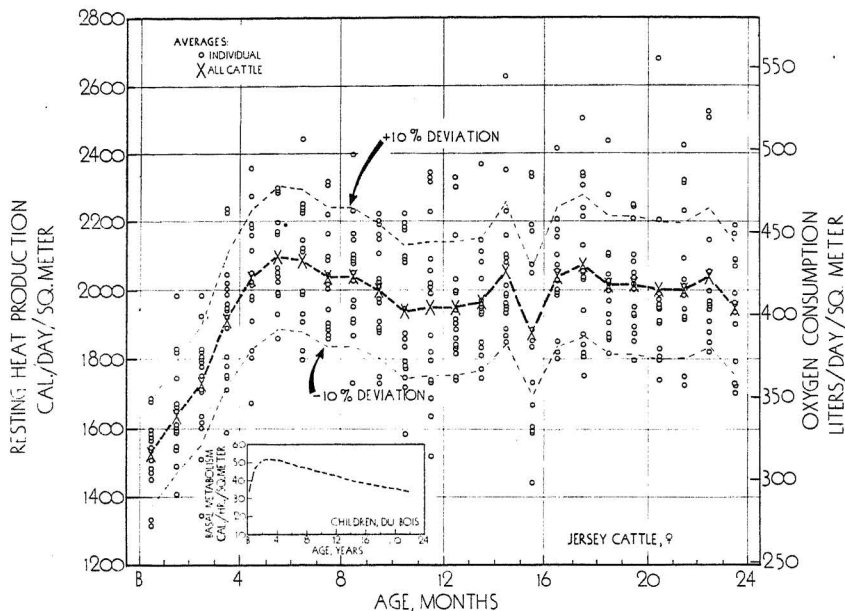


Fig. 4. Resting heat production per square meter of surface area for the 18 Jersey heifers, and also in children (the inset), plotted against age. The surface area was computed from the formula $SA = 0.15 W^{.66}$ in which SA is surface area in sq. meters and W is body weight in kgs. (see pp. 10 Missouri Res. Bul. 89, or pp. 27, Res. Bul. 115).

5 months (about 2000 Cal./Sq. meter) and remains approximately constant at this level to 24 months. The scatter of the data appears wide because the distance 0 to 1200 on the ordinate axis is omitted (to save space). Actually, as indicated by the 10% deviation lines (which include over $\frac{2}{3}$ of the data points), the data are very consistent indeed, especially considering that the measurements were taken at all seasons, on 18 animals born in different months and years, and measured by different persons with different metabolism equipment.

Fig. 5, showing the metabolism per unit area as a function of weight, rises from birth to about 100 Kg, then remains approximately constant.

Attention is directed to the insert, from Du Bois, in the lower-left corner of Fig. 4, showing an early rise in metabolism per unit surface area in children, and its similarity to the early rise in cattle.

Now let us return to Fig. 2. From Figs. 4 and 5 it appears that the curve relating metabolism to body weight has to be split into two segments, one preceding about 6 months, and one following 6 months, as shown by the heavy continuous lines

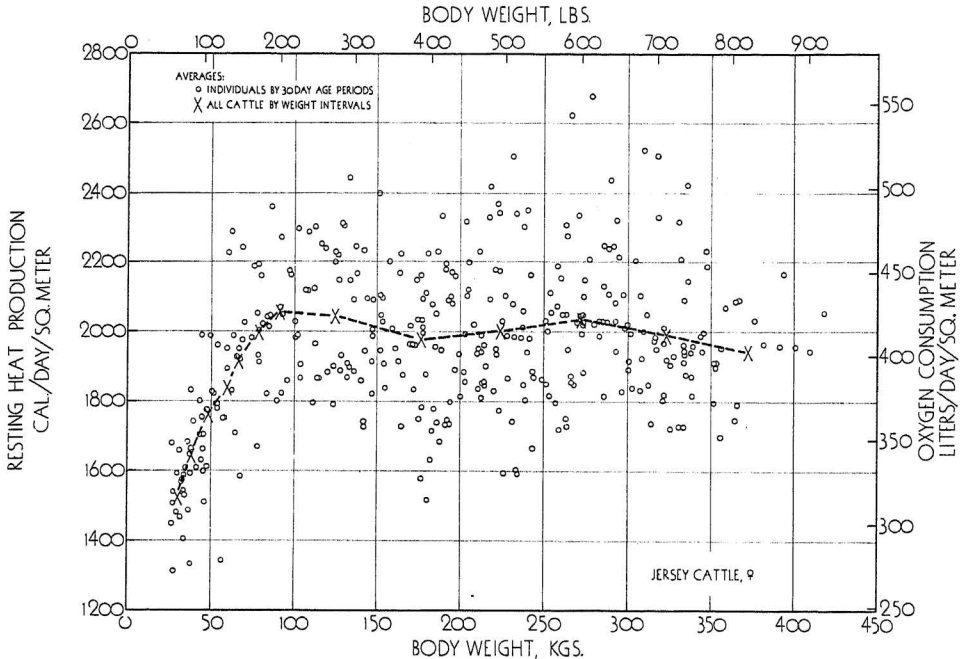


Fig. 5. Resting heat production per square meter of surface area for the Jersey heifers plotted against body weight.

in Fig. 2. Subdividing the data in this manner, the fit of the equation $Y = aX^b$ to the data is excellent, as shown by the small standard errors of estimate, $+Sr$, and $-Sr$ (light broken curves), which include between them $\frac{2}{3}$ of the data.

From the equations of these lines, given on the chart in Fig. 2, it is seen that the slope, b , relating resting metabolism to body weight is 0.56 for the period following 100 Kg., exactly the same as the slope relating surface area to body weight; there is thus no doubt that following 6 months, the metabolism per unit surface area tends to be constant, provided it is agreed—as we observed by actual measurements¹—that surface area increases with the 0.56 (not $\frac{2}{3}$) power of body weight. Preceding 5 months, however, the slope, b , relating resting metabolism to body weight is nearer unity (proportional to body weight) than 0.56 (proportional to surface area).

We next examine Fig. 3 showing the relation of ventilation rate, that is the air volume inhaled or exhaled per minute, to body weight. Here, again, the relative-growth equation $Y = aX^b$ was first fitted to all the data by the method of least squares, with the result shown by the heavy continuous line. Here, too

¹Missouri Agric. Exp. Sta. Res. Buls. 89 (p. 10) and 115 (p. 27).

the early ventilation rate data sag below the general trend represented by the heavy line. However, the deviations are not striking, so that no attempt was made to break up the data into two groups as was done in Fig. 2 for metabolism.

The values of the standard errors of estimate, S_r , are seen to be 2 to 3 times as great for ventilation rate as for metabolic rate. This is as might be expected from the observation that environmental temperature has a much more profound influence on ventilation rate in non-sweating or panting animals, such as cattle, than on metabolic rate.

An especially interesting aspect about Fig. 3, is that the slope of the ventilation curve following 6 months is not 0.56 as for metabolism, but 0.72. This, of course, means that the larger, or the older, the animal the less the oxygen decrement and CO_2 increment in the expired air. This is shown numerically in the last column of Table 1. The ratio of O_2 consumed to air inhaled decreases from 2.2% at 75 kg. body weight to 1.6% at 500 kg. body weight.

Finally, the lowest light broken curve in Fig. 2 represents the *basal* metabolism of *mature* animals of different species. As indicated by the lower-right figures, the basal metabolism of mature animals of different species is considerably below the resting metabolism of our Jersey heifers; and that the slope, b , relating the basal metabolism of mature animals of different species to body weight is 0.73, considerably higher than the slope 0.56, relating the resting metabolism of our Jersey heifers to body weight following 6 months of age. Is this unexpectedly low slope value, 0.56, observed on growing cattle, uniquely characteristic of cattle?

2. Relation of metabolism to body weight in growing man.

—Fig. 2 (also Figs. 4 and 5) indicates the possible presence of a break in the metabolism-weight curve of Jersey heifers at 5 to 6 months of age, that is, at the approximate age of “natural weaning”. Assuming the reality of existence of such a break in the metabolism-weight curve at weaning, one wonders whether this is a unique characteristic of the given cattle, or do other species, for example man, show a similar break at the corresponding physiologic age. This section presents the results of an analysis of the relation between metabolism and body weight in man, for the purpose of throwing light on this question. The results are summarized in Fig. 6, supplemented by Figs. 7 and 8 and by Table 3. See Figs. 7 and 8 for the sources of data.

Fig. 6, like Fig. 2, is a logarithmic coordinate chart; both axes have logarithmic or percentage rather than arithmetic scales. As before, the equation $Y = aX^b$ was fitted to the data

by the method of least squares, and the fitted equations are given on the charts.

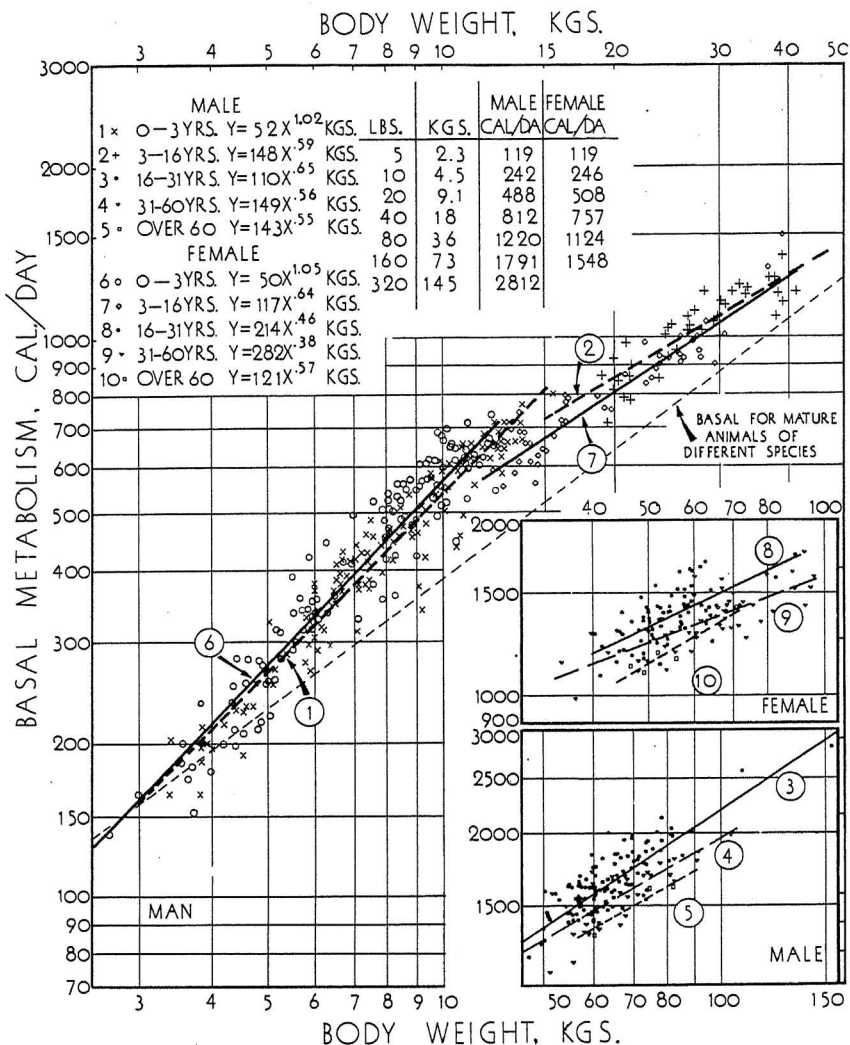


Fig. 6. Metabolism of children, male and female, plotted against body weight. For sources of data see Figs. 7 and 8.

Fig. 6, relating metabolism to body weight in man, shows that:

- 1) The metabolism-weight curve changes in slope at approximately 3 years of age ("natural-weaning" age?).

TABLE 3. "BASAL METABOLISM" PREDICTION TABLE FOR MAN
(From Given Equations, Figs. 7, 8.)

Ages	Body Weight		S Area in Sq. Cm.	Metabolism, Cal/24 hrs.								Energy Metabolism Equivalents in Terms of Quantities* of Milk (4% Fat)			
				Males				Females				Males		Females	
				Total	Per Kg.	Per Lb.	Per Sq. M.	Total	Per Kg.	Per Lb.	Per Sq. M.	Quarts	Liters	Quarts	Liters
Birth	2	4.4	1585	105	53	24	662	104	52	24	656	0.14	0.136	0.14	0.135
to	4	8.8	2593	212	53	24	818	215	54	24	829	0.29	0.274	0.29	0.278
3	6	13.2	3449	321	54	24	931	329	55	25	954	0.44	0.415	0.45	0.426
yrs.	8	17.6	4217	430	54	24	1020	445	56	25	1055	0.59	0.556	0.61	0.576
	10	22.0	4925	540	54	25	1096	562	56	26	1141	0.74	0.699	0.77	0.727
	12	26.5	5588	650	54	25	1163	681	56	26	1219	0.89	0.841	0.93	0.881
	14	30.9	6216	760	54	25	1123	800	57	26	1287	1.0	0.983	1.1	1.035
	16	35.3	6814	871	54	25	1278	921	58	26	1352	1.2	1.127	1.3	1.191
3 to 16 yrs.	16	35.3	6814	760	48	22	1115	690	43	20	1013	1.0	1.0	0.95	0.9
	18	39.7	7389	815	45	21	1103	744	41	19	1007	1.1	1.1	1.0	1.0
	20	44.1	7942	867	43	20	1092	796	40	18	1002	1.2	1.2	1.1	1.0
	25	55.1	9250	989	40	18	1069	918	37	17	992	1.4	1.3	1.3	1.2
	30	66.1	10,470	1101	37	17	1052	1037	35	16	990	1.5	1.4	1.4	1.3
	35	77.2	11,630	1206	34	16	1037	1139	33	15	979	1.7	1.6	1.6	1.5
	40	88.2	12,720	1305	33	15	1026	1240	31	14	975	1.8	1.7	1.7	1.6
	45	99.2	13,780	1398	31	14	1015	1337	30	13	970	1.9	1.8	1.8	1.7
	50	110.2	14,790	1488	30	13	1006	1431	29	13	968	2.0	1.9	2.0	1.9
	16 to 31 yrs.	40	88.2	12,720	1210	30	14	951	1168	29	13	918	1.7	1.6	1.6
45		99.2	13,780	1306	29	13	948	1233	27	12	895	1.8	1.7	1.7	1.6
50		110.2	14,790	1399	28	13	946	1294	26	12	875	1.9	1.8	1.8	1.7
55		121.3	15,770	1488	27	12	944	1352	25	11	857	2.0	1.9	1.9	1.7
60		132.3	16,710	1575	26	12	943	1407	23	11	842	2.2	2.0	1.9	1.8
65		143.3	17,630	1658	26	12	941	1460	22	10	828	2.3	2.1	2.0	1.9
70		154.3	18,530	1741	25	11	940	1510	22	10	815	2.4	2.3	2.1	2.0
75		165.3	19,400	1821	24	11	939	1559	21	9	804	2.5	2.4	2.1	2.0
80		176.4	20,260	1898	24	11	937	1606	20	9	793	2.6	2.5	2.2	2.1
85		187.4	21,090	1974	23	11	936	1652	19	9	783	2.7	2.6	2.3	2.1
90		198.4	21,910	2049	23	10	935	1696	19	9	774	2.8	2.7	2.3	2.2
95		209.4	22,710	2122	22	10	934	1738	18	8	765	2.9	2.7	2.4	2.2
100		220.5	23,490	2194	22	10	934	1780	18	8	758	3.0	2.8	2.4	2.3

31 to 60 yrs.	35	77.2	11,640	1091	31	14	938	1089	31	14	936	1.5	1.4	1.5	1.4
	40	88.2	12,720	1176	29	13	925	1146	29	13	901	1.6	1.5	1.6	1.5
	45	99.2	13,780	1256	28	13	911	1198	27	12	869	1.7	1.6	1.6	1.5
	50	110.2	14,790	1332	27	12	901	1247	25	11	843	1.8	1.7	1.7	1.6
	55	121.3	15,770	1405	26	12	891	1293	24	11	820	1.9	1.8	1.8	1.7
	60	132.3	16,710	1475	25	11	883	1336	22	10	800	2.0	1.9	1.8	1.7
	65	143.3	17,630	1543	24	11	875	1378	21	10	782	2.1	2.0	1.9	1.8
	70	154.3	18,530	1608	23	10	868	1417	20	9	765	2.2	2.1	1.9	1.8
	75	165.3	19,400	1672	22	10	862	1454	19	9	749	2.3	2.2	2.0	1.9
	80	176.4	20,260	1733	22	10	855	1490	19	8	735	2.4	2.2	2.0	1.9
over 60 yrs.	85	187.4	21,090	1793	21	10	850	1525	18	8	723	2.5	2.3	2.1	2.0
	90	198.4	21,910	1851	21	9	845	1559	17	8	712	2.5	2.4	2.1	2.0
	95	209.4	22,710	1909	20	9	841	1591	17	8	701	2.6	2.5	2.2	2.1
	100	220.5	23,490	1964	20	9	836	1623	16	7	691	2.7	2.5	2.2	2.1
	45	99.2	13,780	1160	26	12	842	1060	24	11	769	1.6	1.5	1.5	1.4
	50	110.2	14,790	1230	25	11	832	1125	23	10	761	1.7	1.6	1.5	1.5
	55	121.3	15,770	1296	24	11	822	1188	22	10	753	1.8	1.7	1.6	1.5
	60	132.3	16,710	1359	23	10	813	1248	21	9	747	1.9	1.8	1.7	1.6
	65	143.3	17,630	1420	22	10	805	1306	20	9	741	1.9	1.8	1.8	1.7
	70	154.3	18,530	1479	21	10	798	1363	19	9	736	2.0	1.9	1.9	1.8
75	165.3	19,400	1537	20	9	792	1418	19	9	731	2.1	2.0	1.9	1.8	
80	176.4	20,260	1592	20	9	786	1471	13	8	726	2.2	2.1	2.0	1.9	
85	187.4	21,090	1646	19	9	780	1522	18	8	722	2.3	2.1	2.1	2.0	
90	198.4	21,910	1699	19	9	775	1573	17	8	718	2.3	2.2	2.2	2.0	
95	209.4	22,710	1750	18	8	771	1622	17	8	714	2.4	2.3	2.2	2.1	
100	220.5	23,490	1800	18	8	766	1670	17	8	711	2.5	2.3	2.3	2.2	

*1 qt. of milk= 2.15 lb. (20°C.) = 730 Calories; 1 liter of milk= 1.031 kg = 773 Calories.

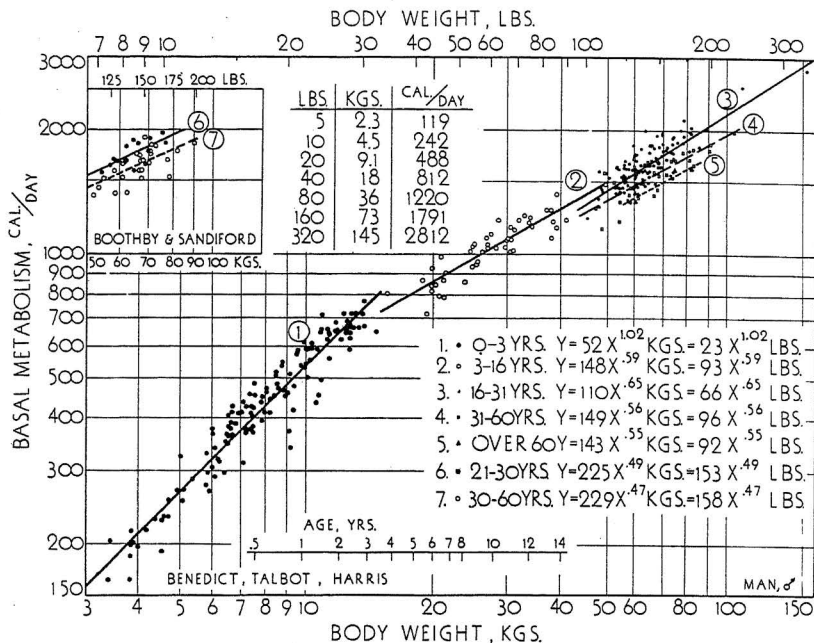


Fig. 7. Metabolism of man, males, plotted against body weight (see Fig. 6).

2) From birth to 3 years the metabolism varies directly with simple body weight; that is, the slope b in the equation $Y = aX^b$ is near unity. The metabolism per unit body weight is, in fact, practically constant, about 52 Cal. per kilo per day, or about 24 Cal. per pound per day. It is interesting to note that extrapolating the equation to intra-uterine growth shows that zero weight and zero metabolism practically coincide, pointing to the possibility that the same equation also represents intra-uterine metabolism. There is no significant sex difference in metabolism per unit weight although the metabolism tends to be slightly higher for girls during this period.

3) Between ages, approximately, 3 and 16 years, the slope of the curve is not 1, as it was prior to 3 years, but about 0.6; the particular data show a slope of 0.59 for boys and 0.64 for girls, and the boys tend to have the higher metabolism for given body weights.

4) Between 16 and 31 years, the slope, b tends to be considerably higher for men than for women—about 0.65 for man and 0.46 for women.

5) Following age 60 years the sex differences tend to disappear.

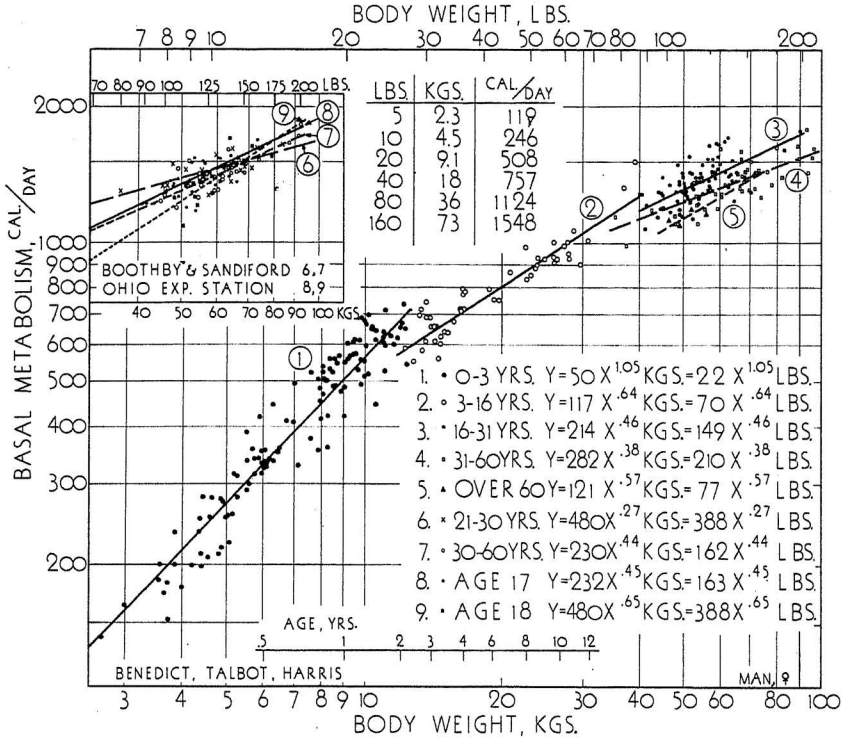


Fig. 8. Metabolism of man, remale, plotted against body weight (see Fig. 6).

The important similarity between our Jersey cattle and Benedict's human data is this: between birth and "natural weaning", the catabolism tends to be directly proportional to simple body weight (the value of b tends to approach unity); following this age, the catabolism tends to vary with the 0.6 power of body weight. Another way of saying the same thing is that prior to "natural" weaning, the metabolism per unit surface area increases; following this age the metabolism per unit area tends to remain approximately constant, or perhaps to decline somewhat (depending on the method of estimating surface area, since surface area is not a precisely determinable entity).

Another observation: the basal metabolism of mature animals of different species tends to increase with the 0.7 power of body weight (see the lowest light broken lines in Figs. 2 and 6); of the same species (cattle or humans) following the age of "natural" weaning, the resting metabolism tends to increase not with the 0.73 but with, approximately, the 0.6 power of body weight. The slope of the curve relating metabolism to

weight is less for growing animals of the same species (following the weaning period) than for mature animals of different species. This is similar to the observation¹ that the slope of the curve relating visceral-organ weights to body weight is less for growing animals of the same species (in the later growth phases) than for mature animals of different species.

3. Historic and explanatory notes.—It is generally known that considerable bodies of data on *basal* and *standard fasting* metabolism of approximately *mature* cattle were obtained at the Pennsylvania Respiration-Calorimeter and the Durham Respiration-Chamber laboratories. No data, however, were previously published on *resting metabolism* of *growing dairy cattle*, collected systematically from birth on, nor on ventilation rates.

It was our original idea² to employ two types of equations for relating metabolism to body size. One for *mature* animals of *different species*

$$Y = aX^b \quad (1)$$

used in this bulletin; another for *growing* animals of the *same species*

$$\frac{Y}{X} = ae^{-kX} \quad (2)$$

used in a preceding report³. In both cases, Y , is metabolism; X , body weight; e , base of natural logarithms; a and b , constants.

As shown in Fig. 2, and also in Figs. 4 to 8, equation (1) can not represent all the data from birth on unless the data are split into two groups; while, as shown in the preceding report³, equation (2) can represent all the data. Equation (2) is thus, in one respect, superior to equation (1) for growing animals. Since equation (2) was not apparently accepted by readers, we return to the use of equation (1), as employed in this report.

While equation (2) may be superior from the viewpoint of precision of representation of all the data, equation (1) is superior from the comparative viewpoints. Thus the use of equation (1) for growth data brings out the fact that following age 6 months in cattle or 3 years in man, the value of the exponent b (the slope of the curve on logarithmic paper) is approximately 0.6 for growing animals of the *same species* as contrasted to 0.73 for *mature* animals of *different species*. The use of two different equations, (1) and (2), would not bring out these differences and similarities.

The following note may serve as a summary of the use of equation (1) in the two preceding reports and an explanation of the meaning of the constants.

¹Missouri Res. Bul. 328.

²Missouri Res. Bul. 166, 1932.

³Id. Res. Bul. 166, 1932.

The basal energy metabolism of mature animals of different species was observed to be represented by the equation

$$Y = 70.5 X^{0.73}$$

in which Y is basal energy metabolism in kilocalories per day for body weight, X, in kilograms. This equation indicates that increasing body weight by 1% increases basal heat production by 0.73%; or doubling body weight increases heat production 73%. This increase in heat production by 73% is in the instantaneous, differential-calculus, sense. The conventional method of computing per cent gives a lower value, about 66%. This equation means that the ratio of heat production Y to body weight X is not constant; but the ratio heat production Y to $X^{0.73}$ is constant, namely 70.5. This equation was reported on pp. 89-97, Missouri Res. Bul. 166, 1932, and p. 12 Res. Bul. 220, 1934.

If the value of the exponent, b, is 0.6 (see Figs. 2, 6, 7, 8) it means that increasing body weight by 100% increases metabolism 60% if computed by the differential-calculus method, but only by 52% if computed by the conventional-arithmetic method. That is, the larger the animal the less the maintenance cost per unit weight.

IV. SUMMARY

This bulletin presents directly-observed data on resting oxygen consumption, and computed data on resting heat production and on ventilation rate of growing Jersey cattle, birth to 25 months (about middle of first gestation). The measurements were made with the animals in a comfortably-lying position before the morning feeding.

Since the volume of carbon dioxide production is roughly equivalent to—actually somewhat lower than—oxygen consumption, this report may also be considered as presenting carbon-dioxide production data. The water vapor exhalation may also be estimated from the air exhaled (ventilation rate) by assuming that the exhaled air is saturated with water vapor.

The ventilation and air-conditioning engineer is thus furnished with important data for oxygen consumption, carbon dioxide production, air exhalation (or inhalation), and water-vapor exhalation, in relation to body weight in growing Jersey cattle under normal conditions of early-morning rest, in the lying position, before the morning feeding.

The student of cattle nutrition and growth is furnished with data on resting maintenance-energy cost of growing Jersey cattle, and especially on the manner of its increase with live weight.

From birth to about 6 months, the resting metabolism (more properly resting energy catabolism) of Jersey heifers varied with the 0.84 power of body weight ($\text{Cal./day} = 88.3 \text{ Wt}_{\text{Kg.}}^{0.84}$); from 6 to 25 months, the resting metabolism varied with the 0.56 power of body weight ($\text{Cal./day} = 295 \text{ Weight}_{\text{Kg.}}^{0.56}$), with exactly the same power found to relate surface area to body

weight (Sq. meter surface area = $0.15 \text{ weight}_{\text{Kg.}}^{0.56}$). The resting metabolism per square meter increased from about 1300 Calories at birth to about 2000 Cal. at 6 months, at which level it remained up to 25 months, the middle of the first gestation period. This contrasts with the basal metabolism of *mature animals of different species*, which tends to vary with the 0.73 power of body weight ($\text{Cal/day} = 70.5 \text{ Weight}_{\text{Kg.}}^{0.73}$). The resting heat production in terms of TDN (total digestive nutrients) was approximately one-half the TDN actually consumed by these growing cattle.

The resting ventilation rate (volume air exhaled or inhaled per minute) in these heifers increased with the 0.72 power of body weight.

In order to test the generality of the observation in cattle that there is a change in the slope of the metabolism-weight curve at the weaning age, an analysis is presented of the relation between metabolism and body weight of growing man (published data by Benedict and associates, and others). In man, the metabolism is directly proportional to simple body weight from birth to 3 years: the metabolism per unit weight is practically constant, about 51 Cal/Kg/day or about 23 Cal/lb/day. Following age three years, the metabolism tends to vary with the 0.6 power of body weight. The metabolism-weight curve in man is thus similar to that of cattle; in both there is a tendency for direct proportionality of metabolism to weight prior to weaning, and for a 0.6 power proportionality following weaning.