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Growth and Development

With Special Reference to Domestic Animals

LXVI. RESTING AND BASAL METABOLISM AND CARDIORESPIRATORY ACTIVITIES IN GROWING MULES

Hudson H. Kibler and Samuel Brody

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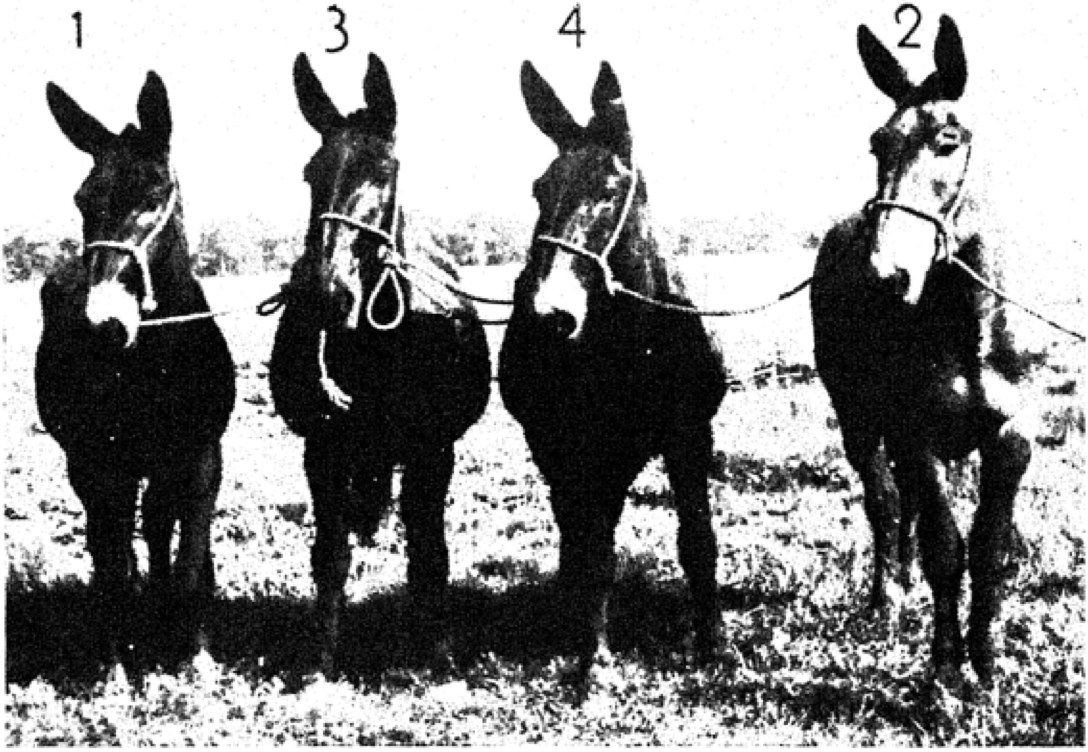

Fig. 1.—The four mules used in this study.

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This bulletin reports the growth and development of four mules from birth to 5 years in respect to changes in body weight, in resting metabolism or heat production (the rate of oxygen consumption and carbon dioxide production while standing quietly) and in cardiorespiratory activities including pulse rate, respiration rate, tidal air (the volume per respiration), and pulmonary ventilation rate (the volume of air respired per minute). Comparable measures on these same four mules while they were working at measured rates in the field were reported previously.[1] Together, these data furnish a scientific basis for comparing the relative economies of mules and other types of farm motive power.

ANIMALS

The four mules are identified by numerals in Fig. 1. Gelding 1 was born April 1; Gelding 2, May 4; Female 3, May 1; and Female 4, April 13, all in 1942. Their Percheron dams (bred to the same sire) ranged in weight from 1300 to 1900 pounds. They were weaned at about 6 months of age and raised together under the same conditions. They were kept on pasture during all but one or two months of each winter, but received supplemental feed when necessary.

The body weight data for the individual animals are plotted in Fig. 2. Considerable differences in body weight developed after the first year, Mule 2 eventually attaining the greatest size. Number 4, relatively light for several years and the first to lose weight when the grass became poor, became almost as heavy as Number 1 in the fifth year. The minor cycles in the rate of gain in body weight (Fig. 2) were associated with seasonal changes in nutritive condition of the pasture. Numerical body weight data interpolated from curves drawn through the plotted data of Fig. 2 are presented in Table 1.

Contribution from the Animal and Dairy Husbandry Departments, Missouri Agricultural Experiment Station. Part of these data were obtained under a cooperative arrangement with the Bureau of Animal Industry, Agricultural Research Administration, United States Department of Agriculture.

[1] Kibler, H. H., and Brody, S., Field studies on cardiorespiratory functions and energy expenditure during work and recovery in mules. Mo. Agr. Exp. Sta. Res. Bull. 394, 1945.

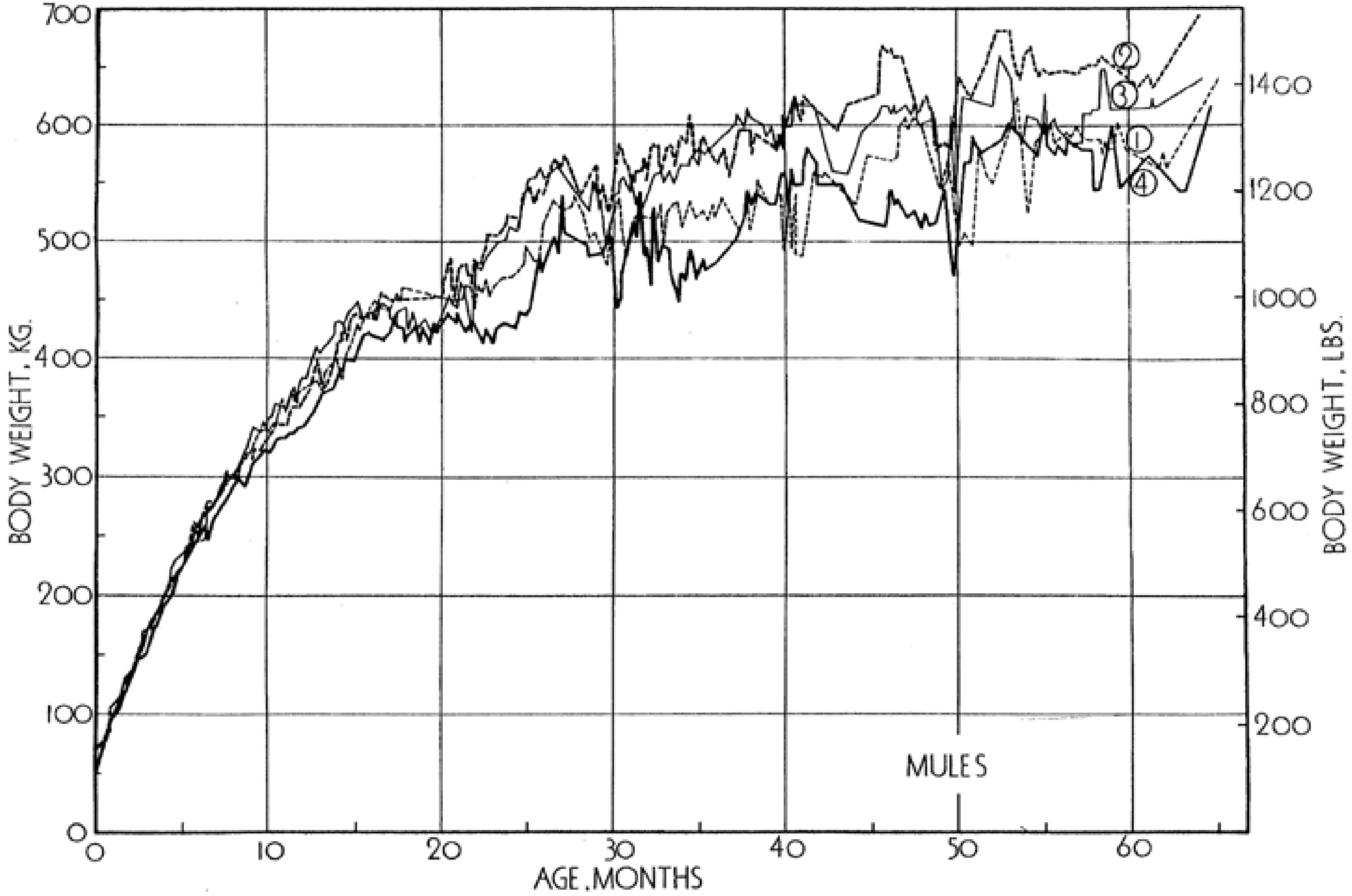

Fig. 2.—Growth curves for individual mules plotted from monthly averages.

TABLE 1.--BODY WEIGHT AND PULSE RATE IN FOUR GROWING MULES*

Age Months	Body Weight, Lb.				Pulse Rate Per Minute			
	Mule				Mule			
	1	2	3	4	1	2	3	4
Birth	108	106	117	114				
1	212	238	216	231		100	88	100
2	298	300	300	287	75	73	70	82
3	375	379	373	348	61	64	65	67
4	448	443	445	425	52	61	62	61
5	511	507	507	494	55	59	59	58
6	573	586	573	551	56	57	57	56
7	626	637	626	591	54	57	55	55
8	675	675	670	644	51	55	54	55
9	734	710	723	683	49	53	53	53
10	769	743	767	714	47	51	52	51
11	802	780	805	743	47	51	52	49
12	833	820	847	772	47	51	52	46
14	882	917	917	860	46	47	47	48
16	974	983	961	924	44	44	42	50
18	1005	1001	957	935	42	44	41	48
20	1003	1019	979	948	41	44	46	47
22	1014	1078	1060	937	40	44	48	47
24	1054	1151	1153	957	39	44	46	47
27	1173	1226	1226	1122	39	39	39	47
30	1151	1235	1182	1089	37	40	36	46
33	1160	1279	1230	1071	40	44	42	44
36	1164	1276	1310	1087	42	45	46	44
39	1177	1310	1318	1197	41	43	42	49
42	1221	1349	1301	1224	37	39	39	48
45	1276	1415	1347	1146	36	38	40	42
48	1283	1349	1314	1146	39	43	45	45
51	1250	1429	1389	1287	42	42	41	51
54	1292	1437	1323	1301	37	38	35	45
57	1296	1440	1345	1265	32	38	35	38
60	1279	1420	1358	1243	34	39	37	41

*The given values of body weight and pulse rate were interpolated from curves drawn through plotted data.

Male mules were castrated May 29, 1943; Mule No. 1 at age 14 months and Mule No. 2 at 13 months.

METHODS

The measurements of resting metabolism, pulse rate, respiration rate, pulmonary ventilation rate, tidal air and rectal temperature were begun within a few weeks after birth. As the mules were on pasture almost continuously, the resting metabolism measures the energy maintenance cost, in the standing position,[2] after intermittent light feeding (grazing). It would appear that these data more nearly represent the normal energy maintenance cost than do basal data, or data taken a given number of hours after a single heavy feeding.

The metabolism measurements were made by the closed-circuit mask method[3] until the mules were 3 years old. In this method, the animal is connected by a mask and large hose to a spirometer previously filled with oxygen and containing a soda lime absorbent for carbon dioxide. As the animal breathes, tracings are made on a clock-driven chart of the respiration rate, the tidal air, and the oxygen consumption rate. The pulmonary ventilation rate was computed from the respiration rate and tidal air.

From 16 months to 5 years of age, measurements were made with an open-circuit mask apparatus.[4] This method allows the animal to breathe normal outdoor air instead of oxygen-rich mixtures. Pulmonary ventilation rate is measured directly by passing the expired air through a large gas meter. The oxygen decrement and carbon dioxide increment are determined by analyses of samples of exhaled air. The resting metabolism is then computed from the oxygen and carbon dioxide data and the pulmonary ventilation rate. This open-circuit method was employed exclusively after the mules were 3 years of age.

As the periods of use of the open-circuit and closed-circuit apparatus overlapped for a year, the resting metabolism data for the two methods can be compared. The statistical tests (Table 7a, b, Appendix) indicate that while there are highly significant differences between the four mules (due to differences in body weight) and in the heat production levels from month to month (due to seasonal effects), the differences between the two methods of measurement are not significant.

The highly significant method-mule interaction (Table 7b, Appendix) probably reflects individual differences in reaction to the closed- and open-circuit apparatus or to their operators; and the highly significant month-method interaction is no doubt caused by unavoidable differences in operating conditions for the closed- and open-circuit tests during certain seasons of the year.

RESULTS

Cardiorespiratory Functions. The general nature of the changes in the cardiorespiratory functions with age is shown in Fig. 3. The irregularities of the monthly averages were subordinated to the seasonal and age trends by plotting three-month moving averages. Easy graphic comparisons were obtained by plotting the data on semi-logarithmic or ratio grids. The abbreviations employed are explained in the legend below Fig. 3.

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[2] A previous publication (Brody, S., Kibler, H. H., and Trowbridge, E. A., Resting energy metabolism and pulmonary ventilation rate in growing horses. Mo. Agr. Exp. Sta. Res. Bull. 368, 1943) reported that there was no difference between standing and lying metabolism records in horses over the entire period of growth.

[3] See Brody, S., "Bioenergetics and Growth", Reinhold, 1945, for a detailed description of the closed-circuit apparatus.

[4] See reference 1 for a detailed description of the open-circuit apparatus.

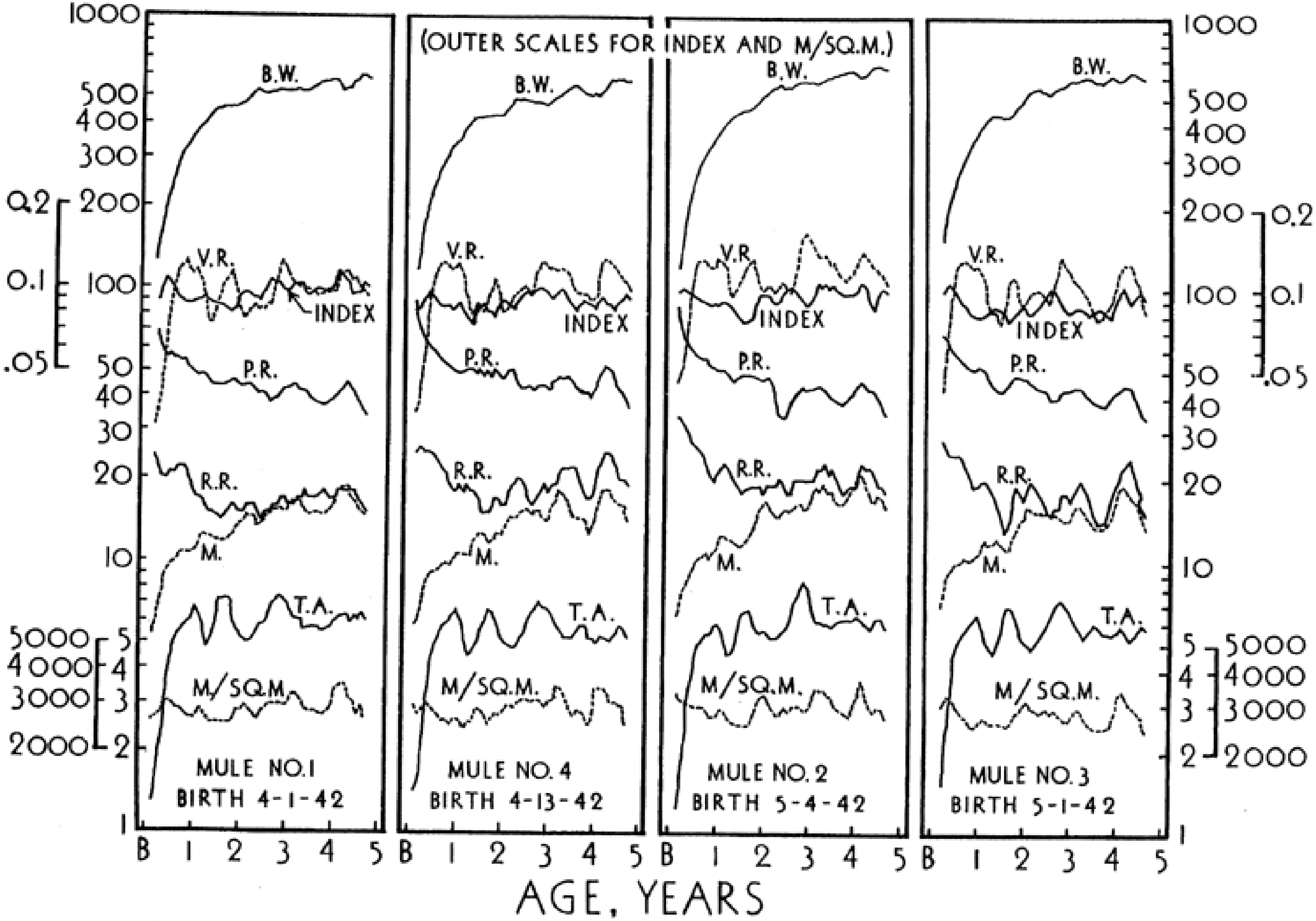

Fig. 3.—Changes with age in (1) body weight (B.W.), kg.; (2) pulmonary ventilation rate (V.R.), lit./min; (3) ml. oxygen/heart beat/kg. body weight (index); (4) pulse beats/min. (P.R.); (5) respirations/min. (R.R.), total energy metabolism/day, mega cal/day or thousands of Cal/day (M); (6) tidal air, lit./min. (T.A.), heat production/unit area, Cal/sq. m./day (M/sq.m.).

The respiration rates in the individual mules declined during the first two years from about 30 to 15 and thereafter rose to 18. The pulse rates decreased continuously over the five-year period.

Clark[5] has demonstrated that in mature animals of different species pulse rate varies inversely with body weight raised to a fractional power. If body weight is expressed in kilograms (instead of in grams, as given by Clark) his equation relating pulse rate, f, with body weight, W, may be written:

$$f = 217\ W^{-0.27}$$

The relation of pulse rate to body weight in the growing mules (Fig. 4) may be expressed by a similar equation fitted to the data of Table 1 (but with body weight in kg.):

$$f = 599\ W^{-0.42}$$

The pulse rates therefore decline more rapidly in growing mules than in mature animals of different species for equal increments of body weight, indicating that age factors as well as body weight factors are involved.

The body weight and resting metabolism increased continuously over the

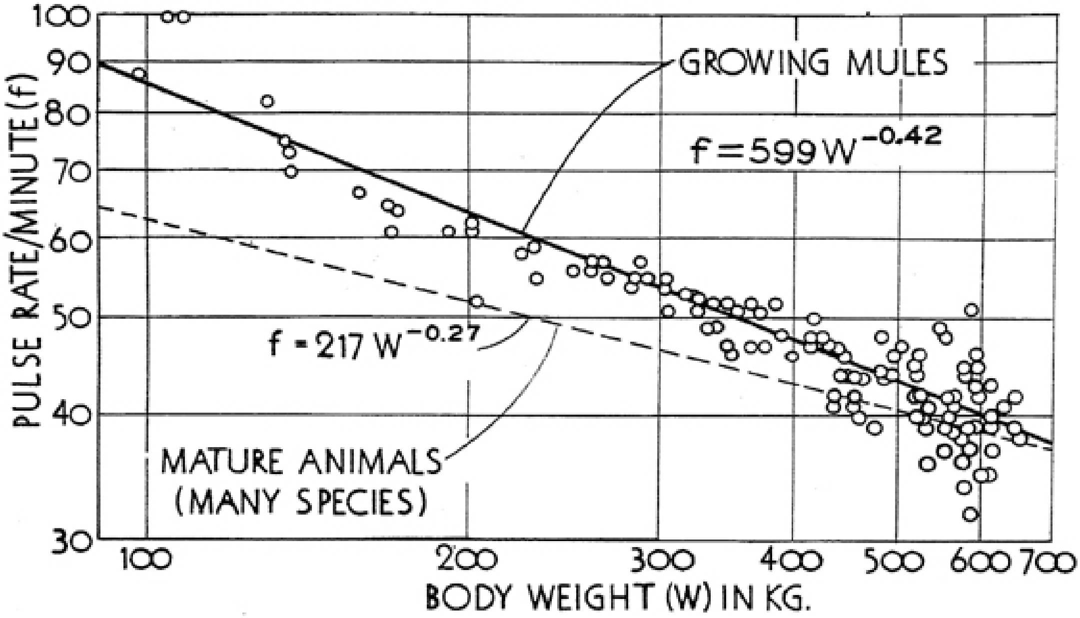

Fig. 4.—Pulse rate per minute in relation to body weight in growing mules. The pulse rate in mature animals of different species (dotted line from Clark's equation) declines with the -0.27 power of body weight. In the growing mules (solid line) the decline is with the -0.42 power of body weight. The more rapid decline of the pulse rate in the growing animals is evidently correlated with increasing age as well as with increasing body weight.

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[5] Clark, A. J., Comparative Physiology of the Heart, p. 89. The Macmillan Co., New York, 1927.

five-year period (Fig. 3). Most of the rise in pulmonary ventilation rate, from about 35 to over 100 liters per minute, and in tidal air, from about 1 to 6 liters, occurred during the first year. The cyclic fluctuations in the age curves of resting metabolism reflect the nutritive condition of the pasture; high metabolic values reflect periods of lush grass when the mules were gaining weight, and low metabolic values reflect periods of poor grass when the mules were losing weight.

The age curves of resting heat production per square meter of surface area (Fig. 3) fluctuate with the seasons but display no appreciable trend. The average values with their standard errors for the individual mules are: 2870 ± 44; 3000 ± 51; 2800 ± 44; and 2900 ± 47 Cal/sq.m./24 hrs.

The pulmonary ventilation rate (Fig. 3) shows marked seasonal influences which are correlated with similar peaks and troughs in the tidal air.

The curves labeled "Index" (Fig. 3) are of interest in connection with a previous report[6] in which it was shown (Fig. 5) that the amount of oxygen consumed per heart beat (oxygen pulse) is directly proportional to body weight in species ranging in body weight from .01 to 5000 kilograms. According to the equation given in Fig. 5, the ratio $\frac{\text{oxygen pulse}}{\text{body weight}} = .06$, indicates that, on the average, mature animals of different species consume 0.06 ml. oxygen for each heart beat per kilogram of body weight. We called this ratio an "index" of work capacity or of cardiac reserve. The values of this cardiorespiratory index tend to be less than 0.06 in inactive animals such as sheep, tame rabbits, and non-athletic men and women; and higher than 0.06 in relatively active animals such as horses, dogs, and athletic men.

In the curves for growing mules (Fig. 3), there is no apparent trend with age in the resting index of cardiac reserve. Over the five-year period, the average values of this index for Mules 1 to 4 are .096, .095, .089, and .090. Since these differences are statistically significant (analysis of variance test), Mules 1 and 2 may be rated superior to Mules 3 and 4 on the basis of cardiac reserve. This result confirms previous ratings based on work tests with these same mules.[7] The absence of age trend in the index of cardiac reserve suggests its predictive possibilities for tests on young animals. Whether or not the $\frac{\text{oxygen pulse}}{\text{body weight}}$ ratios will provide practical rating scales for work capacity and endurance is a problem for further investigation with larger populations of experimental animals.

Relation of Pulmonary Ventilation Rate to Body Weight. Fig. 6 summarizes the ventilation rate data by the closed-circuit method from a few weeks after birth to about four months of age, and from about 13 months to 3 years of age; and by the open-circuit method from 16 months to 5 years of age.

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[6] Kibler, H. H., and Brody, S., An index of muscular-work capacity. Mo. Agr. Exp. Sta. Res. Bull. 367, 1943.

[7] See footnote 1.

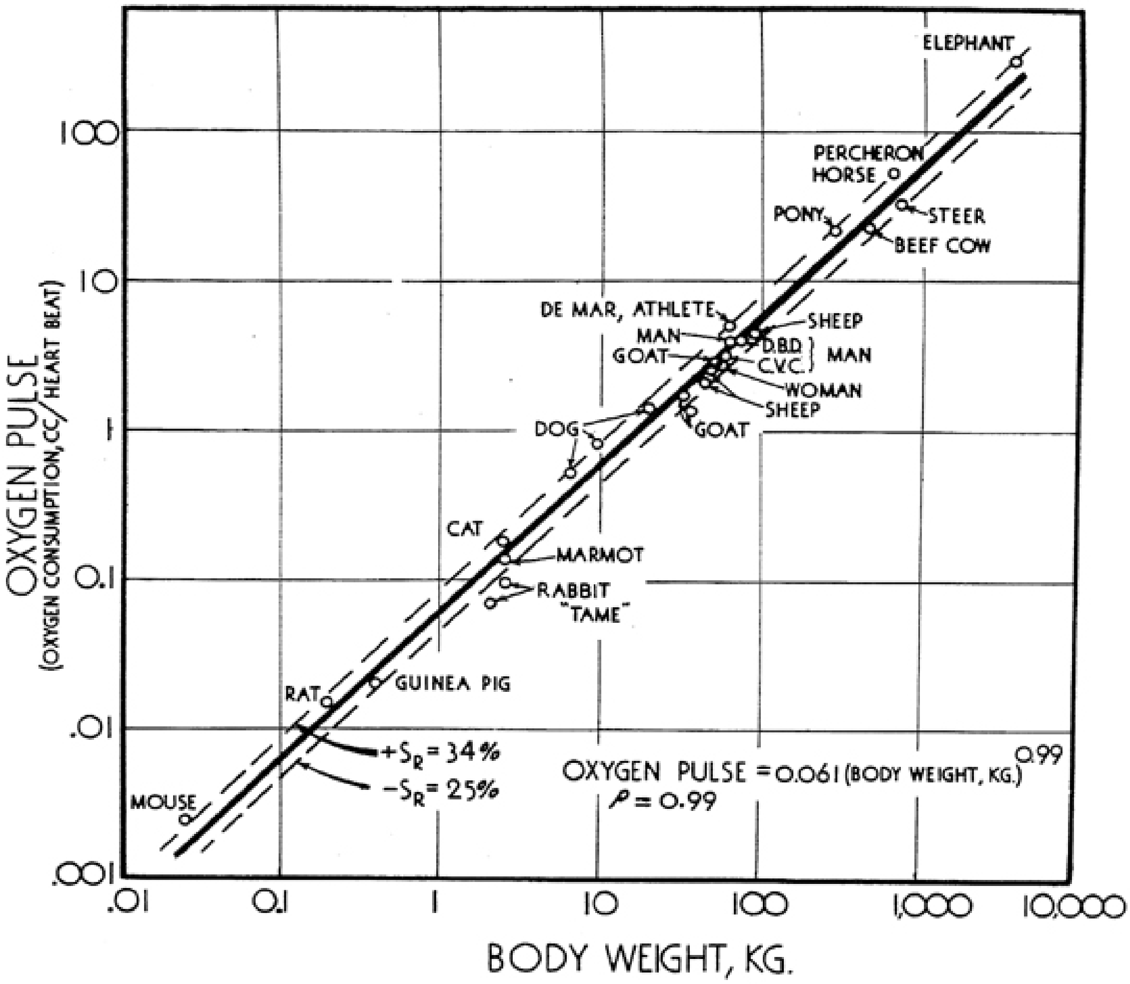

Fig. 5.—Oxygen pulse (oxygen consumed per heart beat) plotted against body weight on logarithmic paper. The regression coefficient is approximately 1, demonstrating that oxygen pulse is directly proportional to body weight in animals of different species. The dash lines represent the standard errors of estimate; part of the variability between species is due to differences in cardiorespiratory capacity and part to differences in experimental conditions. ρ represents the coefficient of correlation. This figure was taken from reference 6.

The lines represent the equation $V = ax^b$ fitted to data for individual animals.[8] The resulting equations and statistical constants are given in Table 2.

The analysis of the ventilation rate data indicates that the coefficients of regression (b) do not differ significantly, but that the levels of ventilation rate for given body weights do differ significantly among the four mules. Mule 2,

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[8] See the section on energy metabolism in relation to body weight for a further discussion on fitting the equation $Y = ax^b$.

TABLE 2.--THE EQUATIONS (FOR FIG. 6.) RELATING PULMONARY VENTILATION RATE AND BODY WEIGHT IN INDIVIDUAL GROWING MULES.

(V = Ventilation Rate, X = Body Weight, in Equation $V = ax^b$)

MULE	NO. OF OBSER-VATIONS	EQUATION		COEFFICIENT OF CORRELATION	STANDARD ERRORS OF ESTIMATE, %	
		V = Lit./Min. X = Kg.	V = Cu. Ft./Min. X = Lb.		+	-
CLOSED CIRCUIT TESTS TO 3 YEARS OF AGE						
1	163	$V = 0.455X^{0.86}$	$V = 0.0081X^{0.86}$	.86	31.2	23.8
2	149	$V = 1.28X^{0.73}$	$V = 0.0253X^{0.73}$	.83	34.1	25.4
3	145	$V = 0.809X^{0.78}$	$V = 0.0154X^{0.78}$	.83	32.1	24.3
4	157	$V = 0.610X^{0.84}$	$V = 0.011X^{0.84}$	.85	30.0	23.1
OPEN CIRCUIT TESTS FROM 1 YEAR 4 MONTHS TO 5 YEARS						
1	181	$V = 0.92X^{0.74}$	$V = 0.0181X^{0.74}$	.38	17.7	15.0
2	166	$V = 1.16X^{0.72}$	$V = 0.0231X^{0.72}$	.44	18.6	15.7
3	207	$V = 0.43X^{0.85}$	$V = 0.0078X^{0.85}$	.47	21.8	17.9
4	201	$V = 0.199X^{1.00}$	$V = 0.0032X^{1.00}$	.55	19.6	17.0
ALL DATA						
	1369	$V = 1.035X^{.73}$	$V = .0205X^{.73}$	.79	28.0	21.8

for example, consistently maintains a higher ventilation rate than Mule 1 for all body weights.

The equation summarizing all data,

$$V, \text{lit/min} = 1.035 \text{ X kg}^{0.73}$$

or

$$V, \text{cu.ft./min} = .025 \text{ X lb}^{0.73}$$

includes 1369 pairs of observations taken by both open- and closed-circuit methods on all four mules. Since there were no significant differences in the regression coefficients of the individual equations, the value of 0.73 obtained for the inclusive equation appears to be a good average value. Predicted ventilation rates for various body weights computed from this equation are given in Table 3.

The standard errors of estimate are large for both the average and indi-

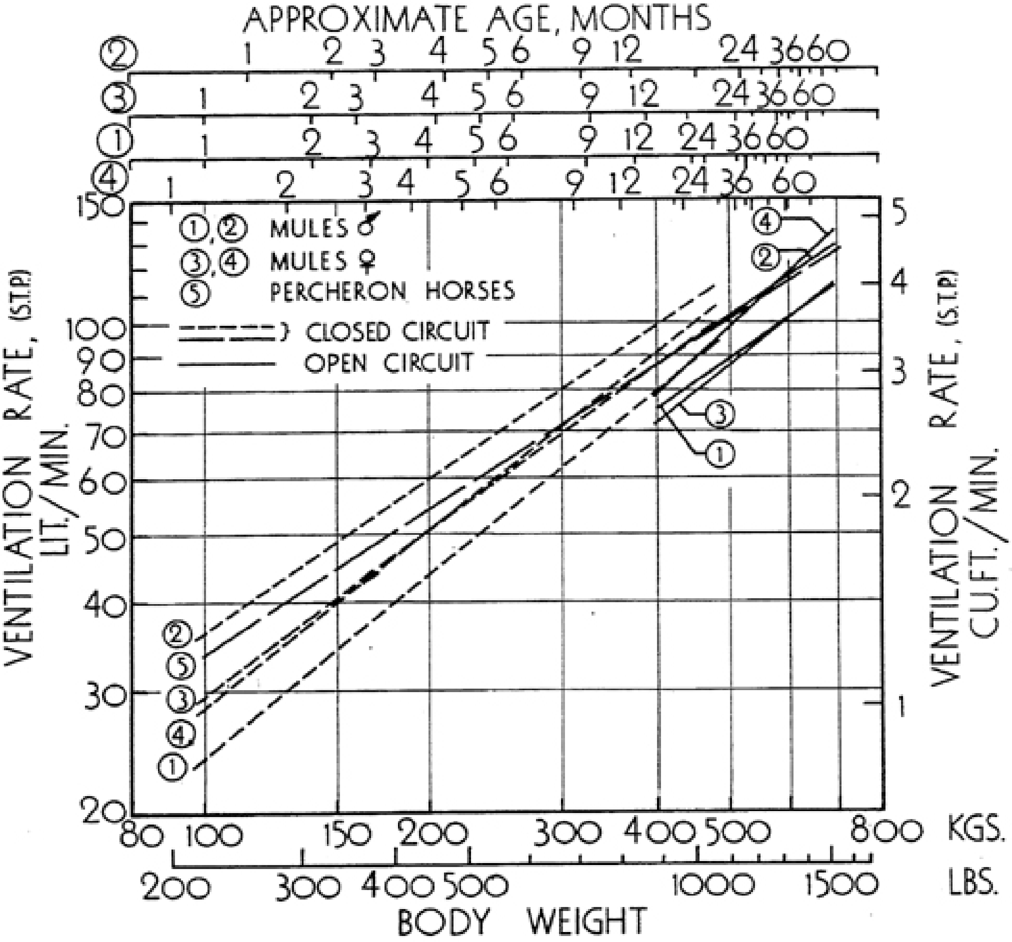

Fig. 6.—Changes in pulmonary ventilation rate with increasing body weight plotted on a logarithmic grid. The equation line for horses includes both females and geldings.

TABLE 3.--PREDICTION TABLE FOR RESTING MAINTENANCE ENERGY COST AND VENTILATION RATE IN GROWING MULES
(Computed from Equations in Figures 7a, b, c and Tables 2 and 4)

Body Weight		Approximate age in Months.	Energy Maintenance Cost per 24 hours							Oxygen Consumption (S.T.P.) Per 24 hours		Ventilation Rate (S.T.P.) Per Min.		Ratio of 02 Consumption to Ventilation Rate
			Calories			B.T.U.								
KGs.	Lbs.		Total[1]	Per Kg.	Per Sq.M.	Total	Per Lb.	Per Sq.M.[2]	Equivalent[3] in TDN lbs.	Liters	Cu.Ft.	Liters	Cu.Ft.	% $\frac{\text{02 Consumed}}{\text{Air Inspired}}$
60	132	.2	3630	60.5	2685	14390	109	10650	1.80	752	26.6	20.8	.73	2.51
80	176	.7	4360	54.5	2686	17300	98	10660	2.40	904	31.9	25.7	.91	2.44
100	220	1.0	5030	50.3	2689	19960	91	10670	2.77	1042	36.8	30.3	1.07	2.39
125	276	1.5	5800	46.4	2690	23020	83	10680	3.20	1202	42.4	35.6	1.26	2.34
150	331	2.4	6520	43.5	2693	25880	78	10690	3.59	1352	47.7	40.7	1.44	2.31
175	386	3.2	7200	41.1	2697	28550	74	10690	3.97	1491	52.7	45.6	1.61	2.27
200	441	4.0	7840	39.2	2697	31100	71	10700	4.32	1624	57.4	50.3	1.78	2.24
225	496	4.8	8450	37.6	2697	33540	68	10700	4.66	1752	61.9	54.8	1.94	2.22
250	551	5.8	9040	36.2	2698	35880	65	10710	4.99	1874	66.2	59.2	2.09	2.20
300	661	7.9	10160	33.9	2701	40320	61	10720	5.60	2106	74.4	67.7	2.39	2.16
350	772	10.9	11220	32.1	2704	44520	58	10730	6.19	2325	82.1	75.8	2.68	2.13
400	882	13.6	12220	30.6	2705	48490	55	10730	6.74	2533	89.5	83.6	2.95	2.10
450	992	19.2	13170	29.3	2705	52260	53	10730	7.26	2730	96.4	91.1	3.22	2.08
500	1102	25.9	14090	28.2	2706	55910	51	10740	7.77	2920	103.1	98.4	3.48	2.06
550	1213	35.7	14980	27.2	2708	59440	49	10740	8.26	3105	109.7	107.2	3.79	1.98
600	1323	38.1	15840	26.4	2709	62850	48	10750	8.73	3283	115.9	112.5	3.97	1.95
650	1433	50.0	16670	25.6	2710	66150	46	10750	9.19	3455	122.0	119.3	4.21	1.97
700	1543	60.0	17480	25.0	2710	69360	45	10750	9.64	3623	127.9	126.0	4.45	2.00

[1] The heat production for the closed circuit data was computed on the assumption that one liter of oxygen has a heat equivalent of 4.825 Calories; and for the open circuit data by using the heat equivalent values corresponding to the experimental respiratory quotients.

[2] Surface area was computed from the equation, surface area in sq. meters = 0.13 (weight in kg.)$^{0.56}$ See Missouri Agri. Exp. Sta. Res. Bul. 115, p. 26.

[3] Computed on the assumption that one lb. TDN (total digestible nutrients) is equivalent to 1814 Calories or one gm. TDN to 4 Calories.

vidual equations, but this is not surprising in view of the several functions performed by the respiratory processes: (1) supplying oxygen and removing carbon dioxide in accordance with the changing metabolic requirements; (2) regulating the acid-base balance in the blood; (3) regulating heat dissipation, in part, by the evaporative cooling of the respiratory tract. These temporary and long-range seasonal adjustments (Fig. 3) produce appreciable variations in the ventilation rate data.

The ventilation rate increases more rapidly than oxygen consumption with increasing body weight. For a 1 per cent increase in body weight, the ventilation rate increases approximately 0.73 per cent while the oxygen consumption increases at rates varying from 0.59 to 0.70 per cent in the four mules (Fig. 7).

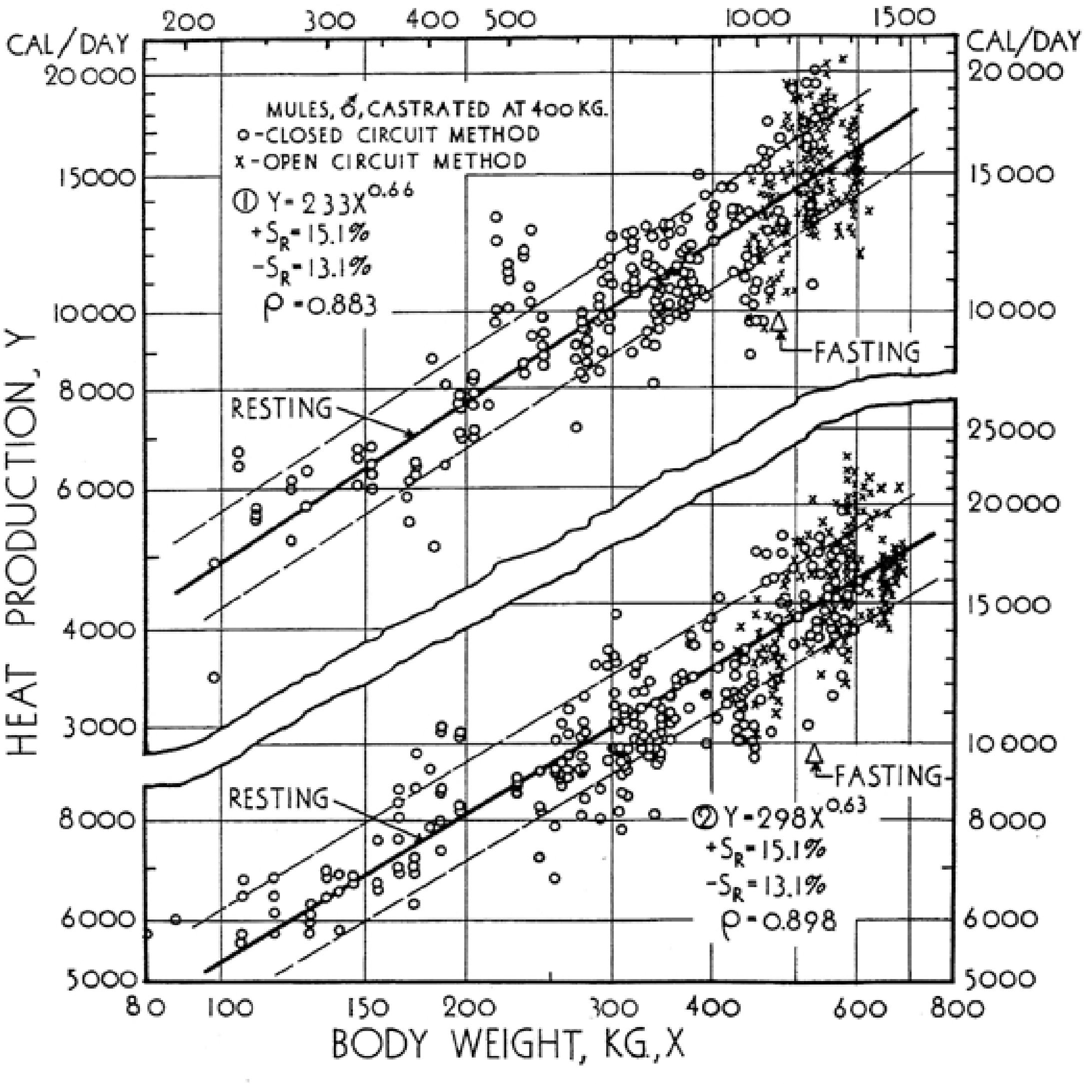

Fig. 7a.—Changes in resting metabolism with body weight in individual male mules plotted on a logarithmic grid.

The ratio of oxygen consumption to ventilation rate is given in Table 3.

By way of comparison, the ventilation rate equation for Percheron horses,[9] measured previously by the closed-circuit method, is shown in Fig. 5. The regression coefficient for the Percheron horse equation is 0.68 as compared to 0.73 for the mules but the general level of the ventilation rate for given body weights is very close to the average for the mules.

Resting Metabolism in Relation to Body Weight in Growing Mules. The resting metabolism is less influenced by seasonal factors (Fig. 3) than is pulmonary ventilation rate, and hence is more highly correlated with body weight. When the data for each mule are plotted separately on logarithmic paper (Figs. 7a and 7b) the individual observations for both the open-circuit and closed-circuit data fall along the same straight lines. The equation

$$\log Y = \log a - b \log X \quad . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

expresses the linear relationship of the logarithms of resting metabolism Y and body weight X. The regression coefficient, b, and the constant, log a, were obtained by fitting equation 1 to all the data for each individual mule by the method of least squares. The fitted equations were then transformed to the usual numerical form

$$Y = ax^b \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

The results are shown in Figs. 7a and 7b; the statistical constants for different units of measurement are given in Table 4.

The differences in resting metabolism between individual mules are statistically highly significant[10] in respect to (1) the regression coefficients (the rela-

TABLE 4.--THE EQUATIONS RELATING RESTING METABOLISM WITH BODY WEIGHT IN GROWING MULES (See Figs. 7a, b, c)

MULE	NO. OF OBSER-VATIONS	EQUATION		COEFFICIENT OF CORRELATION	STANDARD ERRORS OF ESTIMATE, %	
		Y = Cal./24 Hr. X = Kg.	Y = B.T.U./24 Hr. X = Lb.		+	-
		INDIVIDUAL EQUATIONS				
1	482	$Y = 233X^{0.66}$	$Y = 549X^{0.66}$	.883	15.1	13.1
2	437	$Y = 298X^{0.63}$	$Y = 719X^{0.63}$	.898	15.1	13.1
3	478	$Y = 352X^{0.59}$	$Y = 876X^{0.59}$	.837	16.9	14.5
4	483	$Y = 189X^{0.70}$	$Y = 431X^{0.70}$	.880	16.1	13.9
		ALL DATA				
ALL	1880	$Y = 264X^{0.64}$	$Y = 631X^{0.64}$	.872	16.1	13.9

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[9] See reference in footnote 2.

[10] Tested by an analysis of covariance technique. See G. W. Snedecor. Statistical methods, Collegiate Press, Ames, Iowa, 1937.

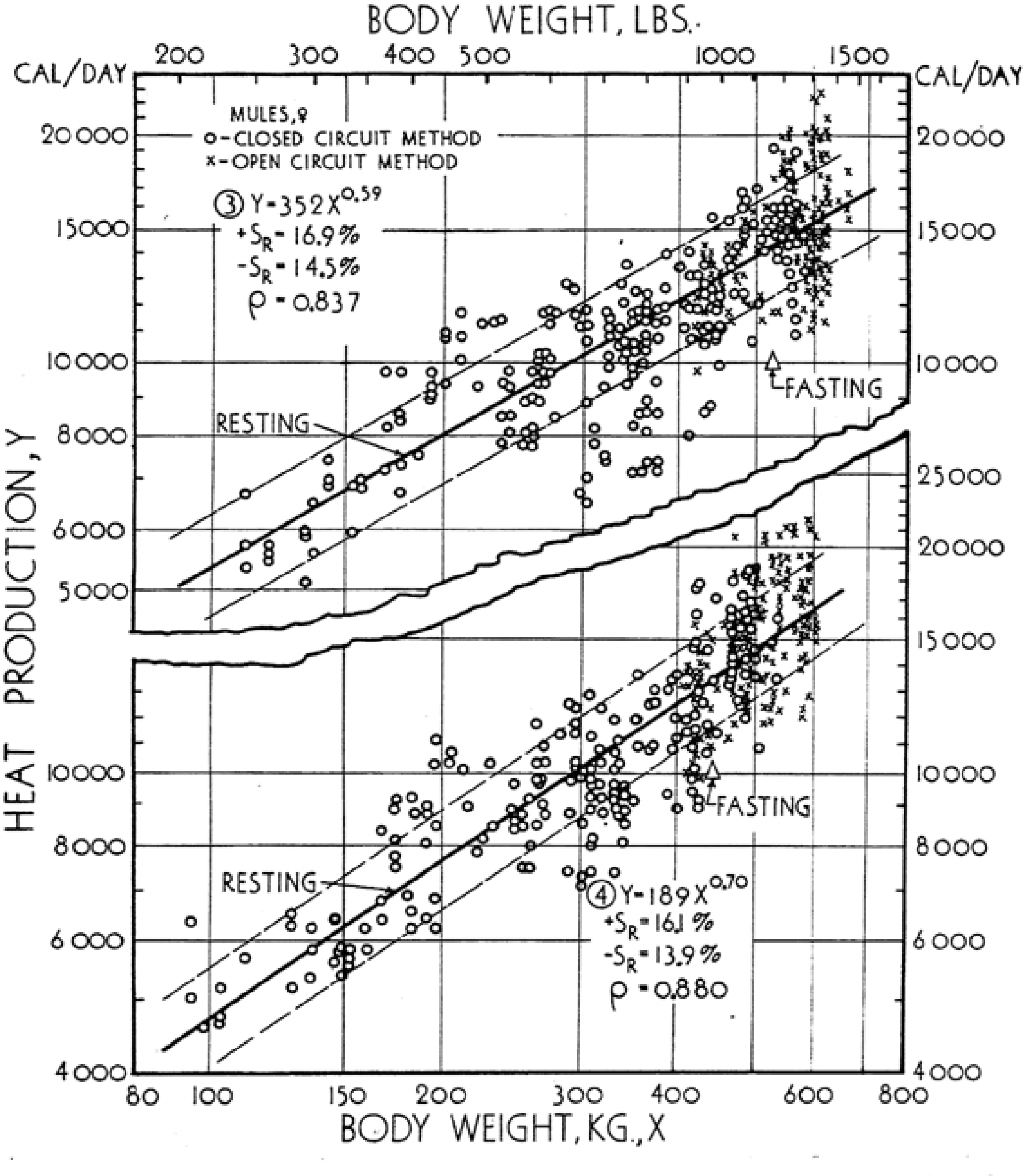

Fig. 7b.—Changes in resting metabolism with body weight in individual female mules plotted on a logarithmic grid.

tive rates of increase in metabolism with body weight, i.e. 0.66; 0.63; 0.59; and 0.70) and to (2) the differences in metabolic levels corrected for body weight differences.

The results of 40- to 60-hour fasts on the resting metabolism and cardiorespiratory functions are given in Table 5. The lowest levels of heat production occurred between the 20th and 44th hours of fasting. The small decreases

TABLE 5.--BASAL METABOLISM (48 - 60 hour fasts) ON FOUR MULES NEAR 2 1/2 YEARS OF AGE.

Date Month and Day	Feed before fast	Body Weight Lbs.	Metabolism Cal./24 Hrs.			Pulse Rate Per Min.		Respiration Rate Per Min.		Pulmonary Ventilation Rate Cu.ft./min.		Tidal Air Cu.ft./min.		Rectal Temp. °F.	
			Rest	Basal	Decrease %	Rest	Basal	Rest	Basal	Rest	Basal	Rest	Basal	Rest	Basal
						No. 1									
8-9	Pasture	1075	13000	10700	17.7	43	29	17	19	59	44	5.6	4.6	99.4	97.8
10-9	Pasture	1110	13500	8700	35.6	32	26	17	11	52	43	7.3	5.3	98.2	99.3
						No. 2									
7-26	Hay	1211	13800	9200	33.4	41	31	21	13	96	52	5.3	4.0	100.6	99.0
8-17	Hay	1198	12100	9000	25.6	36	27	16	9	87	45	6.3	5.0	100.6	97.2
9-20	Pasture	1193	16000	10000	37.5	44	30	16	9	91	51	6.6	5.0	100.2	98.6
						No. 3									
7-26	Hay	1200	14000	9300	33.6	45	33	16	11	69	48	5.0	3.6	100.5	98.8
9-20	Pasture	1167	13700	10000	27.0	40	30	15	8	94	47	6.0	5.3	100.4	97.8
						No. 4									
8-9	Pasture	1023	12300	10000	18.7	45	35	15	14	61	54	4.6	4.3	99.4	99.3
10-5	Pasture	1010	10300	9200	10.7	35	34	9	11	58	53	7.3	4.3	98.3	99.0

[1] The mules were standing when the measurements were made, but as explained in footnote 2 of the text, there is no difference in metabolism between standing and lying measurements. As the tests were made in an open shed, there was no control over temperature.

in heat production for some fasts may be attributed principally to the increasing irritability of the mules with the advance of the fast. The fasting levels of heat production are represented by triangles in Figs. 7a and 7b.

In Fig. 7c the individual equation lines relating resting heat production with body weight are brought together for comparison with each other and with similar data previously reported for horses.[11] The resting metabolism is approximately the same in mules and Percheron horses weighing less than 250 pounds or more than 1300 pounds, but is higher in mules at intermediate body weights. This is because the relative rate of increase in resting metabolism with increasing body weight is constant for the mules but increases sharply at 1100 pounds body weight in the Percheron horses.

While the equations for the individual mules (Table 4) are significantly different in a statistical sense as previously explained, yet for predictive purposes the 1880 observations for all four mules may well be combined without appreciable loss in accuracy of prediction. This combination is effected in the bottom line of Table 4 with little change in the standard error of estimate.

TABLE 6.--OXYGEN CONSUMPTION AND CARBON DIOXIDE PRODUCTION IN FOUR MULES FROM 1 YEAR 4 MONTHS TO 5 YEARS OF AGE BY THE OPEN-CIRCUIT METHOD.

Body Weight		Oxygen Consumption* per minute, S.T.P.		Carbon Dioxide Production* per minute, S.T.P.	
Kg.	Lb.	Lit.	Cu. Ft.	Lit.	Cu. Ft.
450	992	1.86	.066	1.74	.061
500	1102	2.00	.071	1.90	.067
550	1213	2.15	.076	2.05	.072
600	1323	2.29	.081	2.20	.078
650	1433	2.42	.086	2.35	.083
700	1543	2.56	.089	2.50	.088
Constant a		.0220	.000438	.0123	.000228
Regression Coeffiecient b		.726	.726	.811	.811
Standard Error of Estimate		-16.2%	-13.9%	-17.2%	-14.7%

*Computed from equation $Y = aX^b$ fitted to 755 sets of observations, where Y represents oxygen consumption or carbon dioxide production, and X represents body weight. The values of constant a, regression coefficient b, and the standard errors of estimate are shown in the two bottom lines (X is in kilograms when Y is in liters, and X in pounds when Y is in cubic feet.)

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[11] See footnote 8.

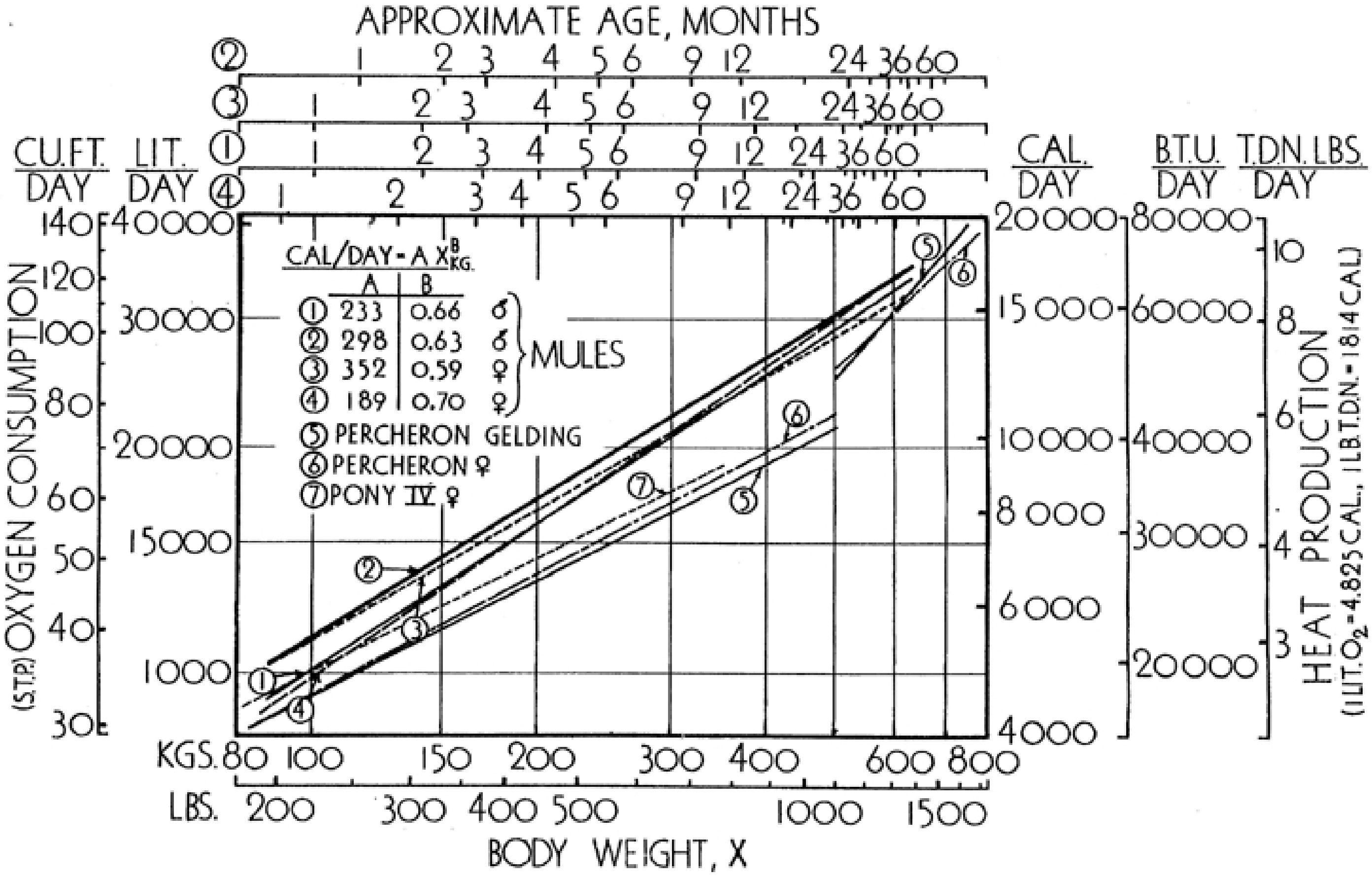

Fig. 7c.—Comparison of changes in resting metabolism with increasing body weight between mules and horses.

The equation fitted to all the data is

$$Y, \text{Cal/24 hrs.} = 264(X, \text{kg.})^{0.64} \quad - - - - - - \quad (3)$$

or

$$Y, \text{B.T.U./24 hrs.} = 631(X, \text{lb.})^{0.64} \quad - - - - - \quad (4)$$

The values of oxygen consumption and carbon dioxide production as related to body weight in mules over one year of age (Table 6) may be of interest to air conditioning and farm building engineers.

DISCUSSION AND SUMMARY

The measurements of *resting* metabolism (O_2 consumption and CO_2 production during rest, but not in post-absorptive condition), pulse rate, respiration rate, tidal air, pulmonary ventilation rate and body weight in growing mules (birth to five years) reported in this bulletin were made in connection with studies on indices of work capacity and endurance in farm workstock. In addition to their importance in relation to the practical problem of developing in early life an endurance index for work stock, these data have considerable interest for comparative developmental physiology and genetics (these being the first such data on mules), and also for developing a fitness index for man.

The differences in the resting metabolism to body weight relation between the mules and the two types of horses (Fig. 7c) would be important if the data on the mules and horses were obtained during the same years, under the same conditions. But since the data on these two categories of animals were obtained in different years and under different conditions the relatively higher values for the mules may be due, in part, to other factors.

The differences in the pulmonary ventilation rates of the individual mules for given body weights are very striking (Fig. 6). The ventilation rate in Mule 2 is about 60 per cent higher at 220 pounds body weight and 15 per cent higher at 1300 pounds body weight than in Mule 1. The rate of change in ventilation rate with increasing body weight is very similar in the mules and horses. The decrease in the ratio of oxygen consumption rate to ventilation rate (last column, Table 3) appears to be correlated with body size and with body temperature regulation. It seems to be a general rule that the larger the animal the more difficult the heat dissipation (because of decrease in surface area per unit body weight), and therefore, the higher the (cooling) ventilation per unit of oxygen consumed.

The ratio of oxygen pulse to body weight, measured in ml. oxygen consumed per heart beat per kg. body weight, is interesting for its possibilities in developing an index of cardiac reserve, or of work capacity. The values of the ratio (resting data) are significantly higher in Mules 1 and 2 than in Mules 3 and 4, confirming the higher work-capacity ratings given Mules 1 and 2 on the basis of earlier work tests. Further tests of this index with larger numbers of animals are needed to establish the utility of this cardiorespiratory index.

Summarizing, the pulmonary ventilation rate in four growing mules increases with the 0.73 power of body weight; the resting metabolism (minimum maintenance energy cost) increases with the 0.64 power of body weight; the pulse rate declines with the -0.42 power of body weight. Average values are given for body weight and pulse rate, and prediction values are given for ventilation rate, resting metabolism in various units, oxygen consumption and carbon dioxide production. The influence of seasonal factors on the cardiorespiratory activities is discussed.

ABSTRACT

Cardiorespiratory data are presented on four mules (2 females and 2 geldings) from a few weeks after birth to 5 years of age. The data include basal and resting metabolism as computed from oxygen consumption and carbon dioxide production (and equivalent T. D. N.); pulse rate; respiration rate; tidal air; pulmonary ventilation rate; and body weight. Comparisons are made with similar data on resting metabolism and pulmonary ventilation rate in growing Percheron horses and Shetland ponies.

The resting metabolism in the four mules increased with the 0.66, 0.63, 0.59, and 0.70 powers of body weight over the five-year period. Fasting 40 to 60 hours depressed the resting metabolism from 11 to 37 per cent below the non-fasting level.

The following equation, fitted by the method of least squares to 1880 paired metabolism-body weight measurements,

Cal/24 hr = 264 (Body weight, kg.)$^{0.64}$ or B.T.U./24 hr = 631 (Body weight, lb)$^{0.64}$ summarizes all the resting metabolism data on the four growing mules.

The corresponding equation for pulmonary ventilation rate, based on 1369 observations is:

$$\text{Lit./min.} = 1.035\ (\text{Body weight, kg.})^{0.73}$$

or

$$\text{Cu. ft./min.} = 0.0205\ (\text{Body weight, lb})^{0.73}$$

The pulse rate in the four mules varies inversely with body weight as indicated by the following equation:

$$\text{Pulse rate} = 599\ (\text{Body weight})^{-0.42}$$

There was no appreciable age trend in the resting heat production per unit surface area. The respective average values with their standard errors for the four individual mules are: 2870 ± 44, 3000 ± 51, 2800 ± 44, and 2900 ± 47 Cal/sq.m/24 hrs.

The respiration rate declined during the first two years from about 30 to 15 and thereafter rose to 18. The tidal air increased to its maximal average value, 6 liters, by the end of the first year.

APPENDIX

The Method Used in Making the Tests of Significance as Summarized at the End of Section on Methods. The resting metabolism data are classified by mule, by month, and by method (closed- or open-circuit) in Table 7a. The differences in resting metabolism between the four mules, the 12 months, and the two methods, as well as the three interactions, are examined for significance in Table 7b.

TABLE 7a.--COMPARISON OF RESTING ENERGY METABOLISM MEASUREMENTS TAKEN BY CLOSED-CIRCUIT AND OPEN-CIRCUIT APPARATUS ON FOUR MULES

	Calories per minute								
Mule	No. 1		No. 2		No. 3		No. 4		Total
Method	Closed	Open	Closed	Open	Closed	Open	Closed	Open	
Month 1944									
Jan.	8.52	8.07	8.77	8.24	8.39	8.39	8.01	8.46	66.85
Feb.	10.28	8.92	11.41	9.04	10.04	9.51	10.78	8.31	78.29
March	9.55	8.81	10.75	11.12	10.08	9.52	10.11	8.47	78.41
April	10.39	8.25	11.07	12.22	10.80	10.01	7.95	7.66	78.35
May	11.39	9.22	12.07	11.25	11.09	12.61	10.29	11.07	88.99
June	11.05	10.57	10.54	12.13	10.75	12.27	10.20	11.35	88.86
July	8.83	9.15	9.29	9.69	8.71	9.37	8.33	9.33	72.70
Aug.	9.68	8.60	7.51	9.38	7.80	8.65	8.39	9.42	69.43
Sept.	9.77	11.07	10.14	11.50	9.50	12.44	10.56	10.33	85.31
Oct.	10.71	9.53	9.90	11.76	10.32	10.78	9.75	9.94	82.69
Nov.	10.79	9.93	10.63	9.91	10.25	10.03	11.01	9.32	81.87
Dec.	10.18	10.27	10.14	11.95	10.73	10.15	10.84	10.49	84.75
Total	121.14	112.39	122.22	128.19	118.46	123.73	116.22	114.15	956.50

TABLE 7b.--ANALYSIS OF VARIANCE OF RESTING ENERGY METABOLISM MEASUREMENTS TAKEN BY CLOSED-CIRCUIT AND OPEN-CIRCUIT APPARATUS ON FOUR MULES

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	Ratio to error
Total	95	135.7968		
Months	11	70.7378	6.4307	14.66**
Methods	1	0.0018	0.0018	.004
Mules	3	10.1958	3.3986	7.747**
Interactions				
Month-Method	11	15.9667	1.4515	3.309**
Method-Mule	3	6.0091	2.0030	4.566**
Month-Mule	33	18.4083	0.5578	1.272
Remainder (error)	33	14.4773	.4387	

**The odds are less than one in one hundred that differences of this magnitude in the ratio of the mean square or variance under test to the remainder mean square could have arisen by chance. The remainder mean square is the best available measure of random fluctuation or error.