Estimation of Heat Production from Heart Rate Measurement of Free Living Farm Animals

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Introduction

The amount of energy in animal products (NE_p) depends on both intake of metabolizable energy (ME) and expenditure of energy as heat production (HP) associated with feeding, production, physical activity and thermoregulation. HP from activity and thermoregulation is influenced by various environmental factors under the farm conditions. The measurement of HP is valuable in understanding the expenditure of energy and the efficiency of animal production.

The basis for measuring HP of animals was established more than a century ago[10]. At present, several methods to determine HP are in common use. However, in most cases these methods restrict the movement of animals during measurement[10]. In 1978, Brockway[2] reviewed the available methods of measuring HP without restraining animal movement and suggested the use of heart rate (HR) to estimate HP. However, in his review[2] there was no discussion of the reliability and limitations of the HR method. Although some other methods such as the carbon dioxide entry rate technique and the doubly labeled water method[10] can also be used without restraining animal movement, the HR method has additional advantages; HR can be measured continuously, relatively easily and at low cost.

The relationship between HR and HP has been stuided in most cases in animals under a walking or exercise load because both HR and HP change widely with these experimental treatments[2,6,15,17]. But it is not appropriate to apply the results of measurement under the load to animals in commercial farm conditions because their circulatory function is different from that under experimental conditions. Some confusions occurred when laboratory results were extended to animals in commercial farms. It is necessary to obtain the reliable and repeatable relationship between HR and HP to be used for free living animals.

The purpose of this paper is to review the application of the HR method for the estimation of HP, and to discuss the extent and limitation of application of experimental results to animals in commercial farm conditions, mainly based on data of our laboratory.

General method

As details are given in the original papers[3-5,14,21,23,24,27], a brief description of some of the methods is given here. HR was measured by means of ECG system. The counting method of HR has been improved from chart recording[21] to digital treatment by a microcomputer[14]. The method of fixing the electrodes on the body surface has been improved to allow measurement of HR continuously throughout the day[14]. On the other hand, the method of HP measurement has developed from the initial use of a simple mask and gas-bag system[21] to head cage[14] or chamber system[27]. McLean's slow- and fast-response methods[10] were used in calculating HP. The latter method was especially useful for the research field[19,23,27,28]. Statistical methods such as correlation and regression analysis were applied[18]. The residual variation of y from the regression line is expressed as a percentage of the mean of y (PE: prediction error, $Sy \cdot x/\bar{y}$, %) and used as the estimate of precision[23].

Result

1) Changes of HR in farm animals

To estimate HP from HR, firstly the characteristic changes of HR in farm animals have to be understood[25]. Examples of the time series of HR in a whole day for cattle and laying hens are shown in Fig. 1. The diurnal rhythm of HR is caused mainly by feed intake for dairy cattle[14,24,26] and by light for laying hens[20]. The continuous high level of HR which occurs in running horse and exercising cattle does not appear in animals kept under normal farm conditions[11,12,14,20,24-26]. Such high HR values shown by some experiments with high work load[6,15,17], may not induce appropriate regression relationship for use under farm conditions.

2) Relation between HR and HP

A time course of HR and HP of a laying hen and high correlation between these parameters is shown in Fig. 2[28]. Similar results have been observed in sheep[19,27] and steers[23]. However, it is not enough for the HR method to get merely a statistically significant correlation between HR and HP, because the pattern of correlation varies with individual animals[1,21,23,30]. To secure general use and validity of the HR method, it is necessary to consider individual animal variation in the regression relationship[21,28], and day to day fluctuation in HR[2,28], as well as any restrictions that may be necessary in applying the HR method under field conditions.

3) Estimation of regression equations for farm animals

(1) Laying hen: Fig. 3 [A] shows all the data of HR and HP of four hens measured simultaneously at one-min intervals, using the fast-response method for measuring HP. An example of such measurements from an individual hen is shown in Fig. 2 [A]. Correlation coefficients obtained from 12 repeated calibrations for each hen showed r=0.86±

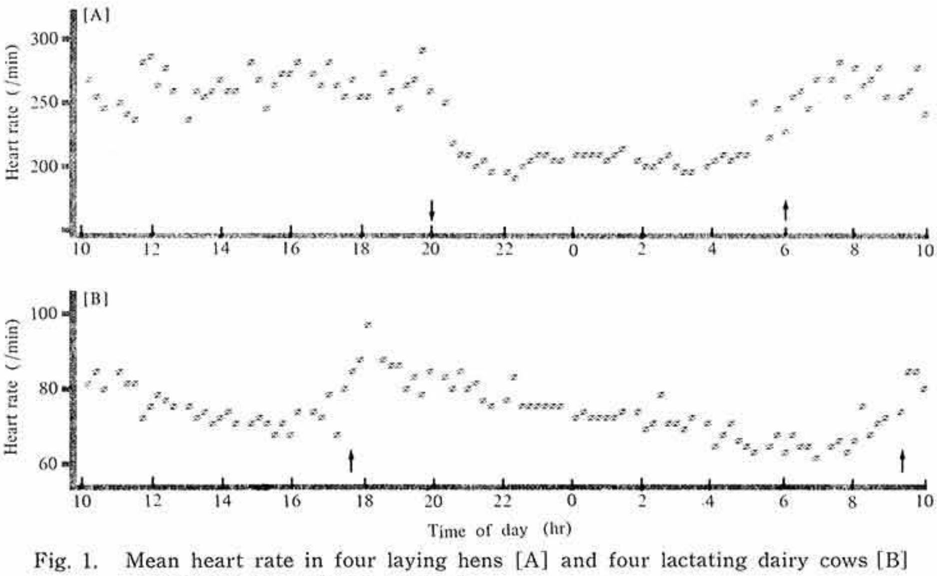

Fig. 1. Mean heart rate in four laying hens [A] and four lactating dairy cows [B] Measured at a 15 min interval.
↓ and ↑ for hens: Light off and on, ↑ for cows: Feed delivery time.

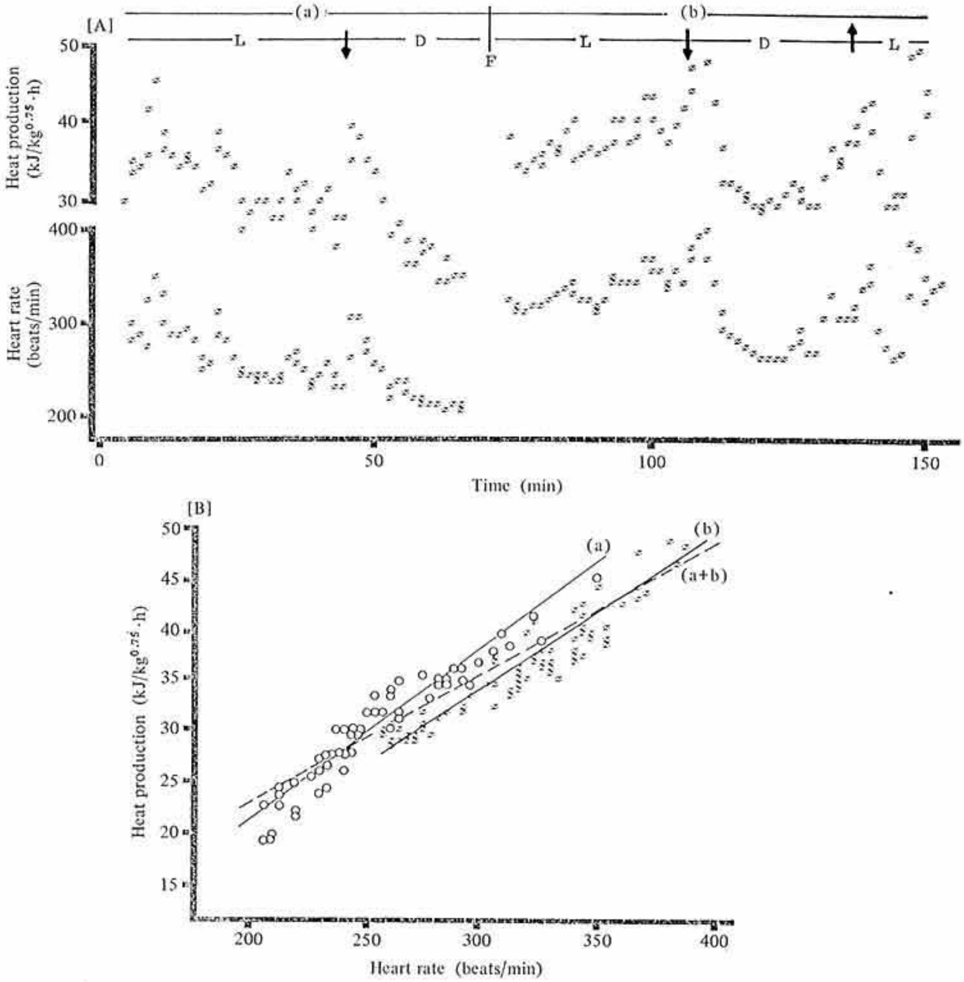

Fig. 2. An example of time series of heart rate and heat production [A], and relationship between them [B] in a laying hen
(a): Before feeding, (b): During and after feeding.
L: Lighting, D: Darkness, ↑↓: Light on and off.
Linear regressions for (a), (b) and (a+b) are as follows:
(a); $Y=-12.55+0.168X$, $PE=\pm5.9\%$, $r=0.95$, $n=61$,
(b); $Y=-11.68+0.152X$, $PE=\pm5.3\%$, $r=0.95$, $n=77$,
(a+b); $Y=-4.36+0.132X$, $PE=\pm6.9\%$, $r=0.94$.

0.08 with low PE (6.67±1.37, %)[28]. However, the relationships varied with an individual hen, with days and with periods before, during and after feeding (Fig. 2 [B]). It was therefore considered necessary to find some means to eliminate these biological variations.

Relative heart rate (RHR), which is the ratio of HR to the basal HR, has been used to eliminate individual and day to day variations of HR. The HR value at the resting time before daily feeding was taken as the basal HR[13,21,22,24]. However, for the results shown in Fig. 3 [B], the value of mean HP of all the measurements (29.37 kJ/kg$^{0.75}$·hr, n=3,053) was used for calculation of the basal HR. Namely, 29.37 kJ/kg$^{0.75}$·hr was put into 48 regression equations to find out the basal HR (HR of 1.0 RHR is 272.9±18.6, beats/min). Thus all 48 regression lines of RHR

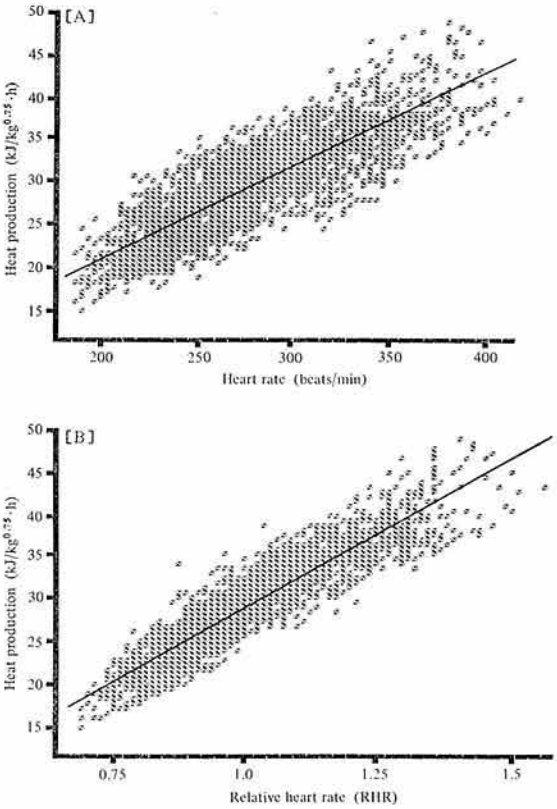

Fig. 3. Relationships of HR to HP [A] or RHR to HP [B] of laying hens
[A]: Y=−0.18+0.107X, PE=±9.9%, r=0.95, n=3,053 (Pooled data of four layers),
[B]: Y=−5.67+34.7X, PE=±7.4%, r=0.92, n=3,053.
HR of 1.0 RHR is 272.9±18.6 beats/min.

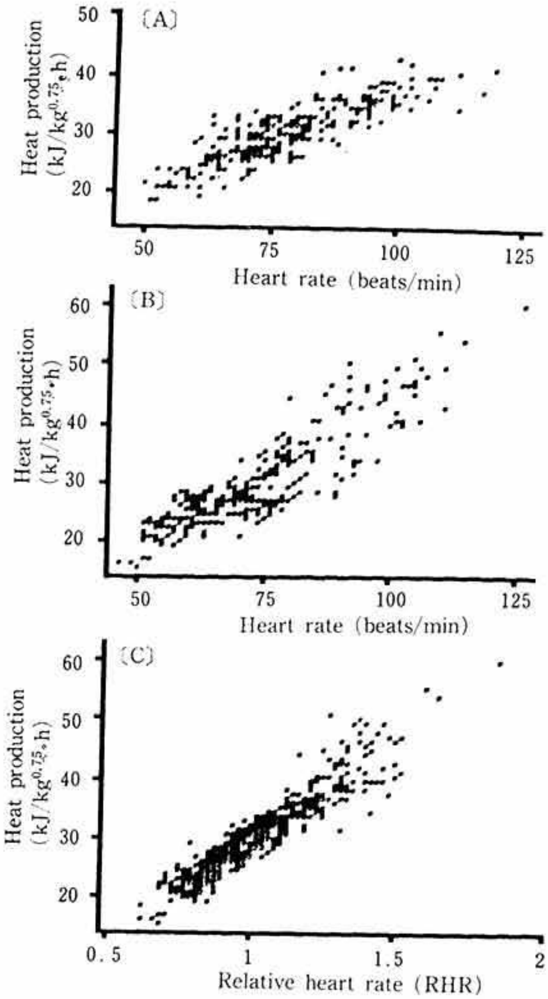

Fig. 4. Relationships of HR or RHR to HP of four Japanese native goats
[A]: Under the condition including before, during and after eating; $Y=5.46+0.318X_{HR}$, PE=±8.1%, r=0.87, n=288,
[B]: Under the condition including before, during and after forced walking; $Y=-4.54+0.437X_{HR}$, PE=±11.9%, r=0.89, n=288,
[C]: Pooled both experimental conditionsA+B; $Y=-3.45+33.19X_{RHR}$, PE=±7.6%, r=0.94, n=576.
HR of 1.0 RHR is 74.9±5.9 beats/min.

and HP passed through the point of 1.0 RHR with a corresponding value of mean HP. The relations between RHR and HP calculated in this way showed reduced variation of HR. Although the RHR correction is very useful in reducing the variation caused by both individual and day to day differences, the suggested equations for estimation of HP are useful only when the mean HR of a group is based on at least four individuals.

(2) Goat: Native Japanese goats were used to observe the relationship between HR and HP under different conditions, i.e., before, during and after eating or before, dur-

ing and after forced walking. This experiment aimed at evaluating the regression relationship between two different experimental conditions and to unify appropriate equations[5].

The results are shown in Fig. 4. Since the levels of HR during walking were designed to be similar to those during eating, the range in the regression relationship was similar among experimental treatments. This also allowed individual difference and difference within individual to be evaluated. The mean values of regression constants between the relating HP and HR for each calibration were different from the mean value of the equation obtained by pooling the data under both experimental conditions. The pooled data gave a smaller regression coefficient and a large PE compared to the mean values from each of the original equations. However, adoption of the RHR correction enabled to improve the value of the regression constant and PE to the same level of each calibration (Fig. 4 [C]). The success of combining the data obtained under two different conditions indicates that the reliable estimation of HP from HR is possible for the animals under free-living, feeding and walking conditions.

(3) Growing pig: Ten sets of calibrations were carried out using four castrated growing pigs, weighing from 35 to 58 kg. The measurement in each calibration was taken during resting, feeding, and also after feeding[4].

As there was no change in the regression coefficient within the growing period, the results were combined (Table 1). The average PE within individuals was about ±6% but individual difference and difference within individual in the regression constants were evident. Thus by pooling data (Table 1), the regression coefficient and PE become smaller and larger respectively than for individual animals. However, the RHR correction was effective in eliminating these unfavorable results. When estimation based on the RHR is to be made, it is necessary to prepare the average HR from at least four animals. It should be recognized that the estimated HP by this method is for a group of animals, not for an individual animal.

(4) Growing and fattening cattle: Calibration of the HR method was carried out

Table 1. Regression constants in equations to estimate HP from HR or RHR for growing pigs weighing from 35 to 58 kg[4]

Animal no.	No. of calibrations (n)	No. of measurements (n)	Heart rate (/min)	Heat production ($kJ/kg^{0.75}\cdot h$)	Regression coefficient (b)*	Intercept (a)*	Correlation coefficient (r)	Prediction error (PE, %)**
1	10	(90)	122.8 (91～167)	31.5 (20～47)***	0.285	− 3.349	0.96	5.8
2	10	(90)	133.1 (100～175)	35.6 (24～53)	0.406	−18.377	0.97	6.3
3	10	(90)	129.4 (95～180)	32.2 (19～48)	0.289	− 5.191	0.96	5.7
4	10	(90)	130.6 (99～181)	30.6 (20～45)	0.230	0.544	0.95	6.7
Mean	4	(360)	129	32.5	0.301	− 6.446	0.96	6.1
Pooled	(1)	360	129	32.5	0.272	− 2.545	0.85	12.1
RHR****	(1)	360	1.0	32.5	37.180 (0.286)*****	− 4.584	0.94	7.7

1.0 RHR=130.1±6.3(HR, mean±SD, beats/min)

* Linear regression Y=a+bX, Y=HP($kJ/kg^{0.75}\cdot h$), X=HR(/min).

** $S_{x\cdot y}/\bar{y}$, %.

*** Range (max～min).

**** Relative heart rate, linear regression Y=a+bX, Y=HP, X=RHR(HR/1.0 RHR).

***** b/1.0 RHR.

Table 2. Regression constants in equations to estimate HP from HR or RHR for calves and steers

Animals	No. of cattle (n)	No. of calibrations (n)	No. of measurements (n)	Heart rate (/min)	Heat production ($kJ/kg^{0.75}\cdot h$)	Regression coefficient (b)*	Intercept (a)*	Correlation coefficient (r)	Prediction error (PE, %)**
Holstein heifer calves, body weight 126(114~143)kg(mean and range)[29]									
Mean	4	4	(80)	102.2 (61~155)	34.5 (21~42)***	0.203	14.043	0.91	5.3
Pooled	4	(1)	80	102.2	34.5	0.165	17.728	0.85	6.8
RHR****	4	(1)	80	1.0	34.5	18.424 (0.182)*****	15.932	0.89	5.8
1.0 RHR=101.2±7.7(HR, mean±SD, beats/min)									
Holstein bull calves, body weight 136(105~165)kg[21]									
Mean	6	6	(120)	81.1 (46~121)	25.6 (16~36)	0.315	0.591	0.94	6.0
Pooled	6	(1)	120	81.1	25.6	0.227	7.269	0.87	9.7
RHR	6	(1)	120	1.0	25.6	24.889 (0.309)	0.725	0.95	6.0
1.0 RHR=80.6±9.5									
Ayrshire steers, body weight 183(167~198)kg[23]									
Mean	4	4	(93)	73.6 (40~113)	24.8 (14~33)	0.224	8.576	0.91	6.8
Pooled	4	(1)	93	73.6	24.8	0.223	8.404	0.92	7.2
RHR	4	(1)	93	1.0	24.8	15.611 (0.216)	8.876	0.93	6.9
1.0 RHR=72.3±3.8									
Ayrshire steers, body weight 249(224~285)kg[23]									
Mean	4	4	(2,759)	—	—	0.258	3.726	0.86	9.0
Holstein fattening steers, body weight 454(405~518)kg[22]									
Mean	6	6	(96)	68.3 (52~ 99)	21.3 (15~36)	0.299	0.791	0.82	8.8
Pooled	6	(1)	96	68.3	21.3	0.328	−1.098	0.87	9.2
RHR	6	(1)	96	1.0	21.3	20.353 (0.295)	0.995	0.89	8.5
1.0 RHR=68.9±2.9									

*, **, ***, ****, ***** See Table 1.

using each cattle from 100 to 500 kg in body weight during rest and before and after feeding[21-23,29]. The result is summerized in Table 2. Although it was possible to estimate HP from HR for individual animal, some problems were found when data from 4 or 6 animals were combined to make a regression equation. For example, the mean regression coefficient values calculated from data taken from several individual animals was clearly different from the regression value derived from the overall pooled data[21]. This was probably due to the large individual difference in HR. Again the RHR correction was useful to solve this problem (Table 2). The mean value of regression constants was also useful to eliminate individual differences.

The above result implies that to estimate HP from HR of an individual cattle, calibration is necessary for each animal[23] and should be made as often as possible. To use the generalized regression equation, an average HR of a group of animals is needed as the basic criterion for using the generalized formulas to estimate HP of that group. In addition, the suitable regression equations should be chosen according to the average and range of HR used in the calibrations as well as the breed and the body weight of cattle.

(5) Dairy and beef breed cows: Special attention is needed in using the HR method

Table 3. Regression constants in equations to estimate HP from HR or RHR for dairy and beef breed cows

Animals	No. of cattle (n)	No. of calib-rations (n)	No. of measure-ments (n)	Heart rate (/min)	Heat production ($kJ/kg^{0.75}\cdot h$)	Regres-sion co-efficient (b)*	Intercept (a)*	Correla-tion co-efficient (r)	Predic-tion error (PE, %)**
Holstein dry cows, prepartum(24～2 days before calving), body weight 670(625～700)kg[3]									
Mean	6	11	(182)	84.0 (56～134)	26.5 (17～33)***	0.251	5.735	0.86	5.4
RHR****	6	(1)	182	1.0	26.5	22.332 (0.260)*****	4.027	0.91	5.8
1.0 RHR=85.8±18.8(HR, mean±SD, beats/min)									
Holstein lactating cows, postpartum(20～39 days after calving), body weight 529(500～564)kg[3]									
Mean	6	9	(144)	71.8 (51～ 93)	34.1 (26～42)	0.557	−5.274	0.91	4.0
RHR	6	(1)	144	1.0	34.1	31.403 (0.443)	2.24	0.91	5.3
1.0 RHR=70.9±5.9									
Holstein lactating cows, mean milk production 15 kg/day, body weight 578(496～721)kg[24]									
Mean	6	6	(102)	75.6 (56～105)	34.2 (23～45)	0.491	−3.031	0.90	6.7
Pooled	6	(1)	102	75.6	34.2	0.384	5.206	0.77	9.8
RHR	6	(1)	102	1.0	34.2	35.822 (0.475)	−1.687	0.90	6.7
1.0 RHR=75.5±6.1									
Holstein lactating cows, mean milk production 27.5kg/day, body weight 605(582～620)kg[16]									
Mean	4	4	(191)	62.9 (39～ 91)	33.7 (23～48)	0.495	2.364	0.90	6.8
Pooled	4	(1)	191	62.9	33.7	0.418	7.382	0.85	8.5
RHR	4	(1)	191	1.0	33.7	30.314 (0.482)	3.386	0.90	7.2
1.0 RHR=62.9±4.4									
Japanese Black (beef breed) cows,									
A. pre-conception to 151 days before calving, body weight 501(457～567)kg[26]									
Mean	7	7	(107)	60.6 (42～ 88)	23.6 (16～33)	0.373	1.047	0.91	7.0
Pooled	7	(1)	107	60.6	23.6	0.356	2.051	0.88	8.3
RHR	7	(1)	107	1.0	23.6	22.018 (0.366)	1.507	0.92	6.8
1.0 RHR=60.1±3.3									
B. latter stage of pregnancy, body weight 541kg[26]									
Mean	2	2	30	90.0 (66～120)	27.7 (20～38)	0.335	−2.470	0.93	6.8
C. lactating period, body weight 506kg[26]									
Mean	3	3	47	70.5 (46～ 96)	30.1 (19～40)	0.322	7.284	0.89	6.7

*, **, ***, ****, ***** See Table 1.

for dairy and beef cows as they may be pregnant or lactating. HR is high during late pregnancy[26] and HP increases as lactation increases[14]. Some relevant data are shown in Table 3. These RHR corrections to the HR method in cows reduce individual differences and day to day differences in each individual.

The regression coefficient might change in the lactating period according to the differences in the level of milk production or feed intake[14]. With beef cows, it seems necessary to divide the reproductive cycle into at least three stages; late pregnancy, lactation, and dry to middle stage of pregnancy[23].

Discussion

1) Necessity and minimum requirement of HR method

Measurement of HP is a requisite factor to understand effects of environment on farm animals and for evaluating efficiency of animal facilities as well as to assess the nutrition requirement and efficiency of animal production. Although several methods to measure HP have so far been developed, they often can not be easily applied to free living animals under ordinary farming conditions. The main advantage of the HR method is that it can estimate or monitor HP of animals during their activities like grazing, and even under special experimental situations.

The HR method is based on the rate of O_2 consumption by animals. The O_2 consumption or the volume of O_2 uptake into the body can be expressed in terms of HR, cardiac stroke volume (SV) and the difference in O_2 concentration between arterial and venous blood (cAO_2-cVO_2) as follows:

$$VO_2=SV\cdot HR\ (cAO_2-cVO_2).$$

We came to the conclusion that it was possible to estimate HP from HR for any individuals. However, VO_2 could be affected by both SV and cAO_2-cVO_2 as well as by HR itself. Hence, the main physiological requirement of HR method is that all of the factors influencing VO_2, except HR, are constant or function as if constant. Therefore, whenever the HR method is used, the limitations of the calibration and the HR measurement should be reported.

2) Correcting individual difference

Experiments on animals are always accompanied by differences within and between individuals. In order to generalize the results and put them into field application, it is necessary to reduce or eliminate these differences. In the present paper, the individual difference in HR was reduced by the RHR correction. In most cases[13,15,22,24], the basal value of RHR (1.0 RHR) can be obtained from HR of resting animals before feeding in the morning. However, sometimes it is difficult to get HR in quiet conditions, and substantial fluctuation occurs in HR between days[2]. It was clearly shown that the best way to avoid these problems is to use our RHR correction[3-5,26,28]. In this correction, all the regressive lines of calibrations passed through the point of 1.0 RHR with the corresponding value of mean HP for all animals. Consequently, differences within and between individuals in HR, or even in O_2 pulse and HP are combined into one term of the equation. In this connection, it is necessary to use the average HR of a group of at least four animals, and hence the estimated HP is for a group of animals.

3) Relation between O_2 pulse and work load condition in calibration

O_2 pulse is the regression coefficient of the estimation equation and expressed as O_2 pulse=SV (cAO_2-cVO_2)/HR. The variation of O_2 pulse in our results can not be explained physiologically, but we found a tendency and characteristic of the O_2 pulse variation relating to the experimental conditions. In the case of muscle work by goats[5], such as loading and exercising, and high lactating period in cows[3,16,24], values of O_2 pulse are high. The increased O_2 consumption can not be compensated for merely increasing HR, so that SV and cAO_2-cVO_2 also apparently increase. It indicates that the HP estimating equations obtained with animals under a given condition can not be applied to animals in other conditions.

4) Limitation for application of HR method

When the HR method is put into application, some limitations must be set. First, when a general equation is to be used, the average HR in the equation must be obtained. We usually obtain it from more than four animals and it is necessary to obtain it from the measurement for an extended time. When the value of average HR thus obtained is similar to the value of HR which was used for formulating the calibration equation, it can best be applied. Because HR is measured over an extended time, various activities of animals can be included, which may eliminate the error in estimation of HP.

Sometimes HP of grazing cattle was estimated using HR classified by cattle behavior, such as standing, lying, etc.[7-9]. However, such HR values should not be adopted, because HP is not determined only by behavior. HP varies greatly with feeding level and time after feeding even with the same behavior. In adopting the RHR method, these factors have to be taken into consideration.

Kato and his co-workers[7-9] attempted to measure the energy expenditure of grazing animals by the HR method without determination of feed intake or daily gain of the animals. In application of the HR method, it is not possible to estimate the energy efficiency of production in grazing animals unless we have a concurrent estimate of the daily ME intake or NEp. In this case, we can estimate not only HP from HR, but also the efficiency of use of ME intake or NEp.

From the above discussion, it is possible to understand the energy balance of free living animals more clearly and that ME intake or daily gain should be studied not only in grazing animals, but also in housed animals under the complete controlled conditions as basic standards.

Summary

Although it is possible to estimate heat production (HP) from heart rate (HR) physiologically, some limitations have been identified for using the HR method. These arise primarily because both HP and HR vary with physiological status such as levels of loading, stages of pregnancy and levels of milk production as well as there are individual animal differences. In this review, some equations to estimate HP from HR measurements of animals are suggested. Some limitations to the calibrate procedure and their application are also discussed.

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