Metabolic heat production and evaporation of poultry

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ABSTRACT Accurate measurements of gas exchange between an animal and its environment is critical in determining metabolic heat production and respiratory functions of broilers. Information on non-invasive methods to measure gas exchange of broiler chicks and chickens under uncontrolled environmental conditions is lacking in the literature. The aims of this study were: (1) to develop an indirect calorimetric system including a hood that allows gas exchange for chickens, (2) to measure gas exchange and respiratory functions (respiration rate, ventilation rate, and tidal volume) of broiler chickens weighing greater than 250 g, and (3) to calculate heat production and respiratory evapora-

tion of the birds based on measured gas and vapor exchanges. We conducted two trials. The first trial involved 6 broiler chicks evaluated for 6 days in 6 different schedules (6 × 6 Latin square). The chicks were kept inside a heat exchanger with a continuous air flow of 150 mL min^{-1}. The second trial involved 12 birds evaluated for 12 days in 12 different schedules (12 × 12 Latin square). Metabolic heat production and evaporation were influenced by live weight of chicks, varying between evaluation days ($P < 0.05$). The respiratory functions (tidal volume, ventilation rate, and respiratory rate) varied between days, and were strongly influenced by live weight of the broilers ($P < 0.05$).

Key words: evaporative heat loss, indirect calorimetry, metabolic-heat production, respiratory functions

INTRODUCTION

Farm-raised broiler chickens have very rapid growth rate, reaching 2 kg between 35 and 40 days of life (Watts et al., 2011). In the process, they undergo many physiological changes, which considerably alter their thermal equilibrium, and they gain and dissipate heat. In addition, the performance and productivity of broilers are affected by air temperature, relative humidity, and air velocity (Giloh et al., 2012). Thermal equilibrium is intrinsically related to environmental conditions which broilers are exposed to. To characterize their homeostasis, it is important to know their metabolic heat production during the rearing period and determine the heat exchange between the animal and the environment (Randall et al., 2008).

The literature contains limited information on the methodology used to determine metabolic heat production and the environmental conditions that the animals are exposed to. For example, Geraert et al. (1996) and

Yahav et al. (2004) measured metabolic heat production by obtaining the difference between energy intake and retained energy. The assumption of this method is that the animals cannot be in the growth phase or subjected to changes in the storage of fat or other body components because it is assumed that there is no change in the structural composition of the organism. Walsberg and Hoffman (2005) used direct calorimetry, which may be more accurate than measuring the difference between the energy in the food consumed and the energy retained. Furthermore, inside a calorimeter, behavioral changes would occur and affect metabolic rate (Randall et al., 2008). Other studies (Walsberg & Hoffman, 2005; Buyse et al., 1998; Nascimento, 2015) used indirect calorimetry in conjunction with a respiratory chamber and facial mask or hood to measure gas exchange. The positive aspect of using a facial mask or hood is that it allows the study of respiratory functions such as respiratory rate, tidal volume, ventilation rate, and evaporative heat loss. Birds have greater respiratory volume in comparison with mammals and respiratory evaporation is an important component of energy balance of these subjects (DaSilva & Maia, 2013). There are no references in the literature
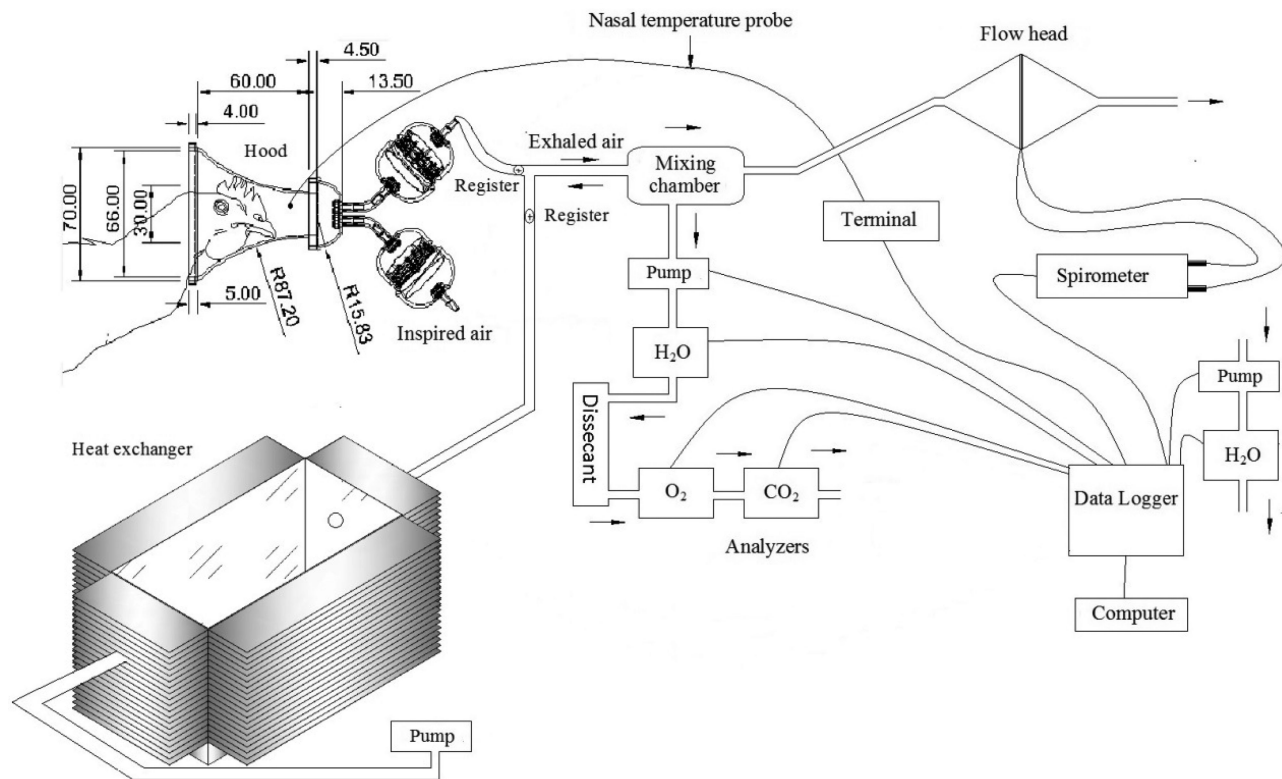
Figure 1. System of indirect calorimetry used for physiological measurements of broiler chickens.

regarding specific methods of determining respiratory evaporation in birds. DaSilva (2008) reported that greater precision would be obtained by isolating a bird's neck from the rest of the body, and suggested use of a non-invasive method. Other earlier studies (Wolf & Walsberg, 1996) used a two-compartment chamber, which may cause behavioral changes in birds. An invasive method, which uses tracheal intubation coupled with pneumotacography was studied by Nightingale (1977) to measure tidal volume.

Collin et al. (2003) measured heat production of broiler chicks between the 10th and 14th days of their rearing period using respiratory cells of indirect calorimetry, which period is distinct from the other rearing periods due to physiological changes they undergo. Kassim and Sykes (1982) obtained respiratory functions of adult domestic fowl by whole body pletismography for air temperatures of 30, 35, and 40°C. Their results, however, cannot be extrapolated to younger birds. Other studies (Brackenbury et al., 1981a; Brackenbury et al., 1981b; Brackenbury et al., 1982) developed a respiratory mask for adult exercising birds to measure oxygen consumption, carbon dioxide production, and water loss through respiration and ventilation. The trials of these studies were conducted in chambers with the birds on a treadmill and exposed to different air temperatures and treadmill velocities. The use of the mask caused no interference on bird movement.

What we could not find in the literature was a methodology that simultaneously measures heat production/loss and respiratory functions during the rearing period of broilers. The limited data available in the literature cannot represent present-day broilers because of their genetic selection. The objectives of this study were: (1) to develop an indirect calorimetric system including a hood to measure gas exchange of broiler chicks and chickens, and (2) to determine respiratory functions (tidal volume, ventilation rate, and respiratory rate) of broiler chickens throughout their rearing period under uncontrolled environmental conditions.

MATERIALS AND METHODS

The experimental protocol was approved by the Institutional Animal Care and Use Committee at the FCAV-UNESP. The research was conducted in the climatic chamber of the Animal Biometeorology Laboratory of São Paulo State University (UNESP), Jaboticabal, Brazil, and the indirect calorimetry system (Figure 1) was developed to measure the metabolic heat production, heat loss by evaporation, and respiratory functions of the birds. Meteorological variables were continuously measured and include air temperature, relative humidity, and black globe temperature using a data logger (U12-013, HOBO, Bourne, MA, USA). These environmental conditions were not controlled but the broilers were protected from direct solar radiation.

A suspended pen (1.5 m^2) was installed in the center of the climatic chamber to accommodate the birds during the trial period using wood shavings as bedding

material. Drinkers and feeders were installed in order to provide water and food ad libitum for the animals.

Broiler chicks during their first seven days of life were put inside a stainless steel heat exchanger (Figure 1) measuring 20 cm long by 10 cm high and 10 cm wide. The heat exchanger was painted black on the inside and painted with acrylic paint on the top. Temperature probes (MLT 422/A, AD Instruments, Australia) were used to measure the temperature inside and outside of the heat exchanger. The temperature of the feathers was measured before placing the chicks inside the heat exchanger with a handheld infrared thermometer (Model 568, Fluke) at a distance of 5 cm. A controlled air flow of 150 mL min^{-1} was pushed through the heat exchanger by a pump (SS4 Sub Sampler, Sable Systems, Paradise, NV, USA). The air going out of the heat exchanger was directed to a flow head (MLT1L, AD Instruments) connected to a Spirometer (ML141, AD Instruments), and the flow rate was compared to that of the pump. The flow rate was calibrated before each data sampling using an 80 mL syringe. After passing through a flow head, the air was directed to a mixing chamber and a small air sample was directed through gas analyzers (FMS-1201-05, Sable Systems) and the percentages of oxygen consumption, carbon dioxide production, and water vapor production of the air going out of the heat exchanger were continuously measured. Data were collected in a data acquisition system (Power Lab 16/30 and Lab Chart Pro, AD Instruments) connected to a computer.

In another experiment, broiler chickens from nine days of age up to slaughter age (43 days) were used for a similar study. In this study, the hood (Figure 1) was a clear and transparent plastic fitted with two valves (26.6 mm diameter), one for the inspired air and the other for the exhaled air (ventilation). A rubber sheet was used to seal the hood around the neck and to avoid any leakage. The exhaled air was directed to the flow head (MLT10L, AD Instruments) connected to the Spirometer and measured the ventilation and respiratory rate of the birds. The air passing through the flow head was directed to a mixing chamber and a small sample was directed to gas analyzers (FMS-1201-05, Sable Systems) to measure percentages of oxygen, carbon dioxide, and water vapor.

During the trials, the broilers were fed two different diets – one from 1 to 21 days of age and the other from 21 to 42 days of age (based on corn and soybean meal with 21.8% and 19.8% crude protein, respectively). The energy of metabolism of the two diets were 3,005 and 3,150 kcal kg^{-1}, respectively. The daily feed intake was similar to that described in the Cobb broiler management guide (Cobb-vantress, 2014).

Physiological Measurements

Metabolic heat production was calculated from measured oxygen consumption, carbon dioxide production,

flow rate going through the heat exchanger (for chicks) or ventilation rate (for chickens) and surface area of the birds and was expressed as (Nascimento et al., 2011):

$$q_{met} = \frac{F\{(0.7633*\Delta O_2*QO_2) + (0.2358*\Delta CO_2*QCO_2)\}}{A_s}$$

where, F is flow rate inside the heat exchanger for broiler chicks or ventilation rate for broiler chickens; ΔO_2 (dimensionless) is the difference between the percentage of oxygen in the atmosphere (O_2 atm) and the percentage of oxygen going out of the heat exchanger or hood, (O_2 h), ((O_2 atm-O_2 h)/100); QO_2 (J L^{-1}) is the caloric coefficient of oxygen; ΔCO_2 (dimensionless) is the difference between the percentage of carbon dioxide going out of the heat exchanger or hood (CO_2h) and the percentage of carbon dioxide in the atmosphere, (CO_2 atm), $\{(CO_2$ h-CO_2 atm)/100\}$; QCO_2 is the caloric coefficient of carbon dioxide. The caloric coefficients of oxygen and carbon dioxide depend on the respiratory quotient (Schmidt-Nielsen, 2002); A_s is surface area of bird which is expressed as 0.000819 (LW$^{0.705}$) (Mitchell, 1930), and LW is the live weight (mass) of chicken.

The heat loss by evaporation was the sum of cutaneous and respiratory evaporation for chicks and only respiratory evaporation for chickens. Heat loss by evaporation was calculated as

$$q_e = \frac{\lambda \left(\frac{F}{1000}\right)(\varphi_E - \varphi_A)}{A_s}$$

where, λ is the latent heat of vaporization of water; φ_A is absolute humidity of the atmosphere; φ_E is absolute humidity of the air going out of the heat exchanger (for chicks) or out of the hood (for chickens). The absolute humidity is expressed as

$$\varphi_A = \frac{2166.87P_p\{T_{air}\}}{T_{air}}$$

where, $P_p\{T_{air}\}$ (kPa) is partial pressure of air; T_{air} is air temperature, and

$$\varphi_E = \frac{2166.87P_s\{T_{he}\}}{T_{he}}$$

where, $P_S\{T_{he}\}$ is vapor pressure of air going out of the heat exchanger (for chicks) or out of the hood (for chickens); T_{he} is temperature inside the heat exchanger, but for the hood case, T_{he} becomes the temperature of the exhaled air, calculated as (Nascimento, 2015)

$$T_{exh} = 22.02 + 0.45T_{air}$$

Experimental and Statistical Analysis

For broiler chicks, a Latin square experimental design (6 chicks × 6 days × 6 schedules) was used. Six day-old chicks from Cobb strain were evaluated in the first six days of their rearing period for six different schedules (from 8:00 to 09:40 h; from 09:40 to 11:20 h; from 11:20 to 13:00 h; from 13:00 to 14:40 h; from 14:40 to 16:20 h; and from 16:20 to 18:00 h). For the broiler chickens, a Latin square experimental design (12 chickens × 12 days × 12 schedules) was used. The 12 rearing period were: 8th, 12th, 15th, 18th, 21st, 24th, 27th, 30th, 33rd, 36th, 39th, and 42nd day of age. The 12 different schedules were: from 8:00 to 08:50 h; from 08:50 to 09:40 h; from 09:40 to 10:30 h; from 10:30 to 11:20 h; from 11:20 to 12:10 h; from 12:10 to 13:00 h; from 13:00 to 13:50 h; from 13:50 to 14:40 h; from 14:40 to 15:30 h; from 15:30 to 16:20 h; from 16:20 to 17:10 h; and from 17:10 to 18:00 h.

Data were analyzed by the least-squares method (Harvey, 1960) using the Statistical Analysis System (SAS Institute, 2009) as a time optimization tool and the adjusted means were compared by Tukey post hoc test ($P \leq 0.05$). The models were:

$$Y_{ijkmn} = \mu + L_i + B_{j(i)} + D_{k(i)} + S_{m(i)} + e_{ijkm}$$

where, Y_{ijkmn} is the nth observation of the metabolic heat production and total or respiratory evaporation; L_i is the fixed effect of the i-th trial (i = 1 – for chicks, i = 2 – for chickens); $B_{j(i)}$ is the fixed effect of the jth chicken inside the ith trial (j = 1,..., 6 – for chicks; j = 1,...,12 – for chickens); $D_{k(i)}$ is the fixed effect of the kth day of the rearing period inside the ith trial (k = 1,...,6 – for chicks; k = 8, 12, 15, 18, 21, 24, 27, 30, 33, 36, 39, 42 – for chickens); $S_{m(i)}$ is the fixed effect of the mth schedule inside the ith trial (m = 1, from 8:00 to 09:40 h; 2, from 09:40 to 11:20 h; 3, from 11:20 to 13:00 h; 4, from 13:00 h to 14:40h; 5, from 14:40 h to 16:20 h; 6, from 16:20h to 18:00 h – for chicks; m = 1, from 8:00 to 08:50 h; 2, from 08:50 to 09:40 h; 3, from 09:40 to 10:30 h; 4, from 10:30 to 11:20 h; 5, from 11:20 to 12:10 h; 6, from 12:10 to 13:00 h; 7, from 13:00 to 13:50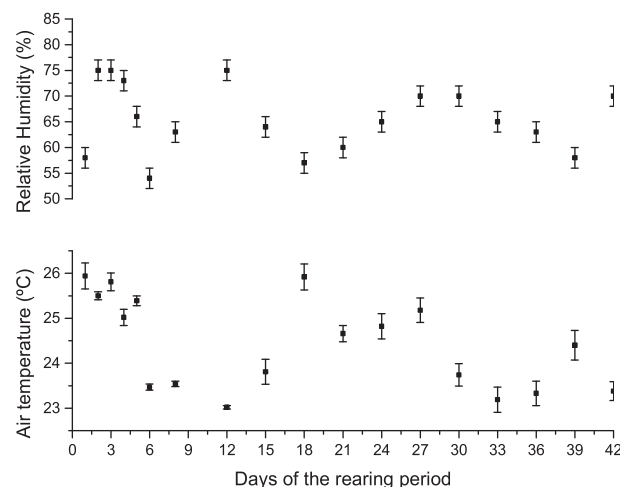 h; 8, from 13:50 to 14:40 h; 9, from 14:40 to 15:30 h; 10, from 15:30 to 16:20 h; 11, from 16:20 to 17:10 h; 12, from 17:10 to 18:00 h – for chickens); e_{ijkm} is the random error.

$$Y_{ijkl} = \mu + C_i + D_j + S_k + e_{ijk}$$

where, Y_{ijkl} is the lth observation of ventilation, tidal volume and respiratory rate; C_i is the fixed effect of the ith chicken (I = 1, …, 12); D_j is the fixed effect of the jth day of the rearing period (j = 1, …, 12); S_k is the fixed effect of the kth schedule (k = 1, from 8:00 to 08:50 h; 2, from 08:50 to 09:40 h; 3, from 09:40 to 10:30 h; 4, from 10:30 to 11:20 h; 5, from 11:20 to 12:10 h; 6, from 12:10 to 13:00 h; 7, from 13:00 to 13:50 h; 8, from 13:50 to 14:40 h; 9, from 14:40 to 15:30 h;

Figure 2. Environmental conditions (relative humidity and air temperature) during the trial as a function of days of rearing period.

10, from 15:30 to 16:20 h; 11, from 16:20 to 17:10 h; 12, from 17:10 to 18:00 h); e_{ijk} is the random error.

RESULTS AND DISCUSSION

Air temperature varied from 25.2°C to 26.3°C and the average relative humidity during the six-day trial was 67%. For the subsequent trials until the 42nd day, air temperature varied between 23°C and 26°C and the average was 24.08 (± 0.10)°C. For relative humidity, the average was 65% (Figure 2). The variation of air temperature was because of uncontrolled environmental conditions during the trial and the birds were kept in a climatic chamber protected from solar radiation. The mean radiant temperature was similar to that of air temperature during the experimental period. The environmental conditions was challenging to the broiler chicks because they are highly sensitive to low temperature in their first days of life (Malheiros et al., 2000). On some days, it was also challenging for the chickens because the air temperature was higher than the comfort-zone temperatures described in the literature, which is between 21°C and 24°C (Macari and Furlan, 2001).

Metabolic heat production differed between trials and days inside the Latin squares ($P < 0.05$); whereas evaporation (total for chicks and respiratory for chickens) differed in all cases ($P < 0.05$, Table 1).
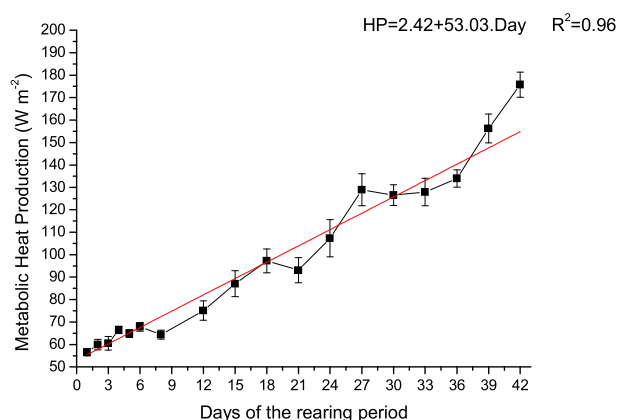
Metabolic heat production of the chicks was significantly lower in the first day of the rearing period ($P < 0.05$) in comparison to all the other days (Figure 3). The metabolic heat production of the chicks increased from 56.62 ± 1.64 W m^{-2} on the first day of age to 67.89 ± 1.90 W m^{-2} on the sixth day. Collin et al. (2003) reported a heat production of approximately 70 W m^{-2} for broiler chicks with an average live weight of 136 g. Their study was based on measurements inside a respiratory cell under a controlled temperature of 29°C, which was considered to be a thermoneutral condition. Similar results were reported by Kita et al. (1993) for broilers weighing 71.4 g with an average daily

Table 1. Mean squares of metabolic heat production (q_{met}), evaporation (q_e), ventilation (V), tidal volume (TV), and respiratory rate (RR) of Cobb broiler chickens.

Source of variation	Degrees of freedom	q_{met} (W.m^{-2})	q_e (W.m^{-2})
Trial	1	46,802.66*	1.91*
Broiler (trial)	17	343.07[NS]	0.60*
Day (trial)	16	7,568.24*	1.96*
Schedule (trial)	16	219.79[NS]	0.55*
Residual	117	284.93	0.21
R^2	–	0.87	0.68
Coefficient of variation (CV)	–	16.41	25.27

Source of variation	Degrees of freedom	V (L.sec^{-1})	TV (mL.resp^{-1})	RR (breaths.min^{-1})
Broilers	11	0.000005[NS]	0.00007[NS]	423.24*
Schedules	11	0.000004[NS]	0.00004[NS]	126.76*
Days	11	0.0005*	0.0013*	998.95*
Residual	110	0.000003	0.00003	97.64
R^2	–	0.94	0.82	0.62
Coefficient of variation (CV)	-	16.16	39.34	16.92

*significant ($P \leq 0.05$); [NS]non-significant ($P > 0.05$).

Figure 3. Averages of metabolic heat production (W m^{-2}) calculated by the least-squares method of Cobb chickens in the rearing period. Least-square regression line: R^2 = 0.96

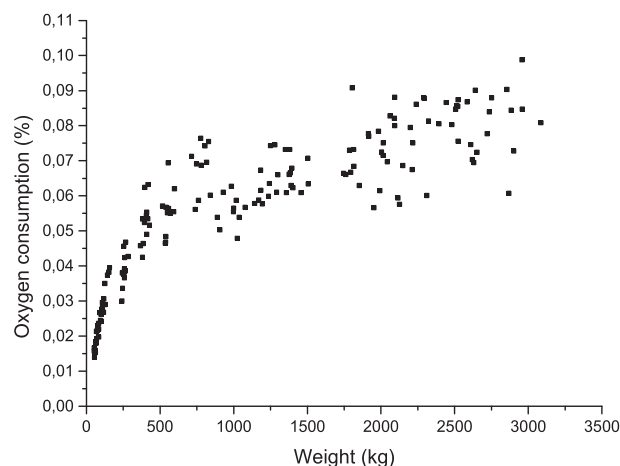**Figure 4.** Oxygen consumption of broiler chickens as a function of body weight.

gain of 6.4 g at the 7th day of the rearing period lasting 10 days. They reported an average heat production of 67.46 W m^{-2} for birds kept in individual metabolic cages at an average controlled temperature of 29°C.

In this study, the regression analysis of the data showed that metabolic heat production increased linearly (R^2 = 0.96) from the 1st to the 42nd day of the rearing period (Figure 3). Higher metabolic heat production was observed at the 42 days of age and that could be because of increased live weight. Figure 4 shows the relationship between oxygen consumption and body weight, and the relationship is non-linear. Oxygen consumption and thus metabolic heat production increased with increasing body weight.

Metabolic heat production was correlated (Figure 5) against live weight (mass) of chicks and broilers for all the trials, and the relationship was linear (R$^2_{aj.}$ = 0.79). The equation that best described heat production as a function of body weight is expressed as

$$ HP = 60.65 + 0.04LW $$

where is heat production, LW is live weight.

Chepete and Xin (2002) proposed an equation for broilers fed ad libitum reared at a thermoneutral environment ranging in temperature between 19°C and 30°C. The equation by Chepete and Xin (2002) was based on data collected 30 years ago. It is important to note that present-day birds have different feed conversion rate, higher feed intake, and better performance than birds reared 30 years ago. Figure 6 compares metabolic heat production calculated in this study to those obtained from Chepete and Xin (2002). According to Chepete and Xin (2002), heat production is approximately constant with increasing body weight and is much lower compared to our results. Figure 6 also includes heat production calculated from metabolizable energy of the diet consumed by the birds. First, it is possible to confirm that the equation proposed by Chepete & Xin (2002) underestimates the heat production of broilers (Figure 6). Our results are close to those predicted by the feed intake.

The total heat loss by evaporation was different between days of both trials ($P < 0.05$). However, the heat loss by this venue was very small (Figure 7). The chicks were kept in an environment where the average
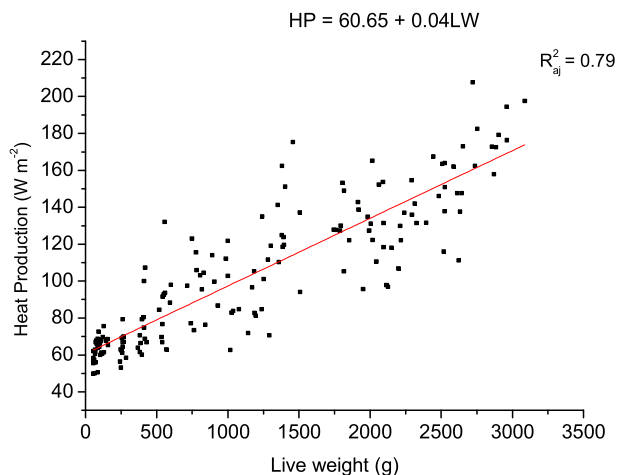
Figure 5. Metabolic heat production (W m^{-2}) as a function of live weight of Cobb broiler chickens. Least-square regression line: R^2 = 0.79.

Figure 7. Total and respiratory evaporation of Cobb broiler chickens during the rearing period calculated using the least-squares method.
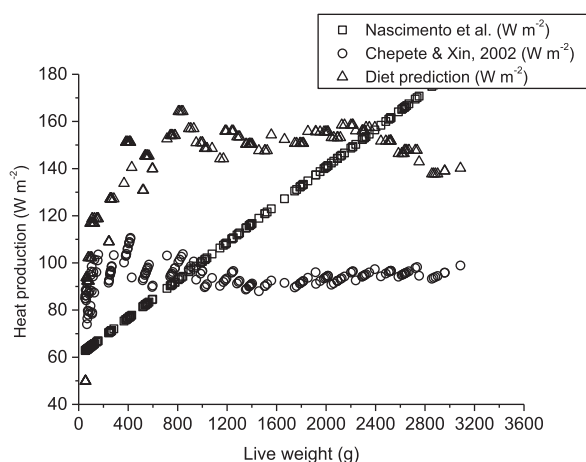

Figure 6. Heat production (W m^{-2}) of Cobb broiler chickens measured in the trials compared to that of Chepete and Xin (2002) and that calculated from the diet intake as a function of body weight.

Figure 8. Respiratory rate and ventilation rate of Cobb broilers as a function of days of rearing period.

temperature was 26.5°C, which is lower than the thermoneutral condition (29°C) reported by Collin et al. (2003). Therefore, the chicks were losing heat to the environment mostly by long wave radiation and convection. The heat loss by respiratory evaporation of broilers was small because the birds were kept at low air temperature. For this reason, there was no observed panting. Richards (1977) reported a latent heat loss of 5.1 and 43.4 W m^{-2} for hens kept at temperatures of 0°C and 38°C, respectively. He also reported a latent heat loss of 21.5 W m^{-2} at an air temperature of 25°C for laying hens with an average weight of 2.28 kg.

In this study, live weight of the broilers increased linearly. Live weight of the birds was approximately 250 g at the 8th day of age and approximately 2,800 g at the 42nd day of age. The respiratory functions of the broiler chickens (ventilation, tidal volume, and respiratory rate) were significantly different ($P < 0.05$) between days. The respiratory functions are intrinsically related to live weight of broilers (Table 2).
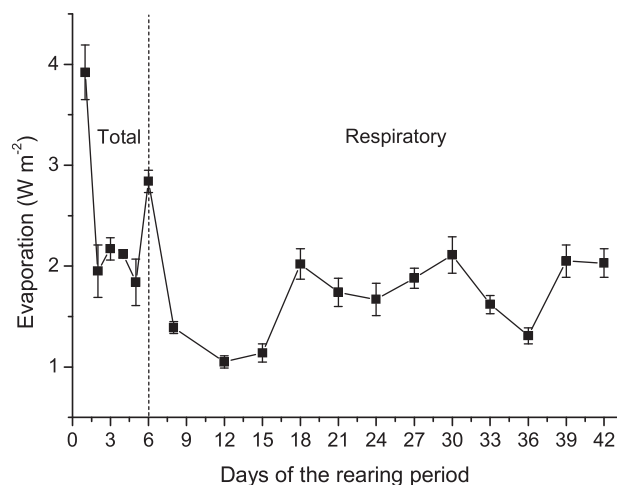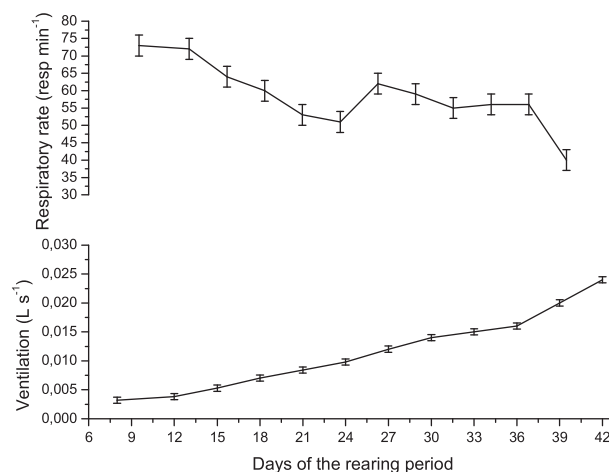
Ventilation rate (volume per breath) exhibited a linear relationship with live weight (Figure 8). Live weight and ventilation rate depend on respiratory rate. The data shows that the higher ventilation rate at the 42nd day of the rearing period corresponded to the lower respiratory rate, and the lower ventilation rate (at the 8th day of life) corresponded to the highest respiratory rate (Figure 9). This suggests that ventilation rate increases as a result of deeper or faster respiratory rate (Powell, 2000). The same was observed for minute volume (Figure 10). Minute volume increased linearly with increasing live weight of broilers. King and Payne (1964) reported approximately 800 mL min^{-1} of minute volume for male broilers with an average live weight of 4 kg. The average respiratory rate was 17 breaths. min^{-1}.

Kassim and Sykes (1982) used whole body pletismography to determine tidal volume, ventilation rate and minute volume of laying hens weighing 2.2kg for air temperature of 20°C and raising progressively to 30, 35 and 40°C, totaling 180 minutes of exposure to 30° and 35°C and 140 minutes to 40°C. The authors reported a
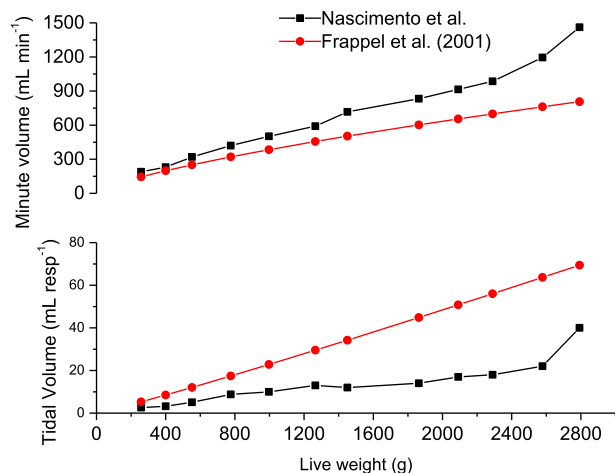
Figure 9. Minute volume and tidal volume of Cobb broiler chickens as a function of live weight.
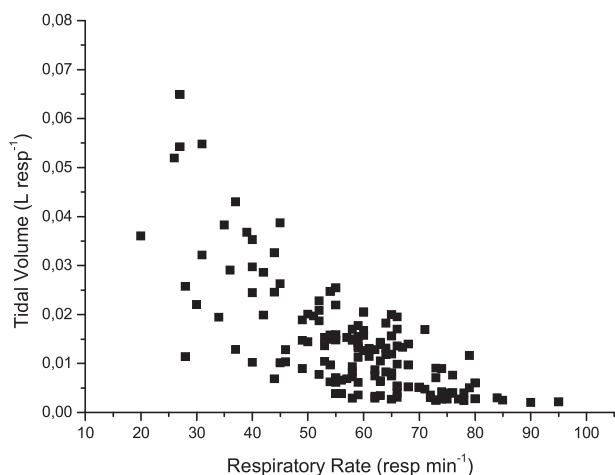

Figure 10. Tidal volume of Cobb broiler chickens as a function of respiratory rate.

minute volume of 574 mL min^{-1}, an average respiration rate of 23 resp. min^{-1} and an average tidal volume of 25.6 mL resp^{-1} for an air temperature of 20°C.

Frappel et al. (2001) developed allometric equations for minute volume and tidal volume for birds of several species. The minute volumes reported by Frappel et al. (2001) were lower than the results obtained in this study (Figure 9). The tidal volumes were, however, higher as shown in Figure 9. It should be pointed out that the equations developed by Frappel et al. (2001) were based on a variety of measuring techniques including mask pneumotachography and volumetric and barometric plethysmography. The conditions of these two studies were also different such as hour of the day (circadian rhythm), illumination level, and nutritional state.

Tidal volume depends on respiratory rate. As the respiratory rate increased the tidal volume decreased (Figure 10). Kassim and Sykes (1982) reported a similar relationship between respiratory rate and tidal volume for laying hens.

CONCLUSIONS

The following conclusions can be drawn from this study:

(1) An indirect calorimetric system including a hood that allows measurement of oxygen consumption and carbon dioxide production was developed. The system can be used in controlled or uncontrolled environmental conditions, and works well without the birds being anesthetized.
(2) Metabolic heat production of broiler chickens increased linearly with increasing body weight, and heat loss by evaporation was low for air temperatures ranging between 23° Cand 26°C for the entire rearing period.
(3) Respiratory functions of broiler chickens were closely related to body weight showing an increase in ventilation rate and tidal volume during the rearing period. Tidal volume was inversely proportional to respiratory rate.

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