UNIVERSIDADE ESTADUAL PAULISTA "JÚLIO DE MESQUITA FILHO" FACULDADE DE CIÊNCIAS AGRÁRIAS E VETERINÁRIAS

CÂMPUS DE JABOTICABAL

NET ENERGY FOR MAINTENANCE AND ALLOMETRIC EXPONENT FOR POULTRY

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Zootecnista

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DADOS CURRICULARES DO AUTOR

RONY RIVEROS LIZANA – filho de Rosa Mercedes Castillo e Alonso Riveros Garcia nasceu no dia 07 de setembro de 1993, no Perú. Em janeiro de 2011 ingressou no curso de Zootecnia na Universidad Nacional Agraria La Molina (UNALM), Lima, Perú. Desde o primeiro semestre da graduacao foi bolsista da Unidad Experimental de Avicultura da Universidad Nacional Agraria La Molina (UNALM), Lima, Perú. Em Descembro de 2016 obteve o título de Bachellor Science em Zootecnista sob orientação do Prof. Dr. Carlos Niceas Vilchez Perales. Em março de 2017 iniciou o curso de pós-graduacao em Zootecnia na Faculdade de Ciências Agrárias e Veterinárias da Universidade Estadual Paulista “Júlio de Mesquita Filho”-Campus de Jaboticabal (FCAV/UNESP) com um projeto de pesquisa envolvendo frangos de corte e com bolsa Capes sob orientação da Profa. Dra. Nilva Kazue Sakomura, defendendo a dissertação em fevereiro de 2020.

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ENERGIA LIQUIDA DE MANTENÇA E EXPONENTE ALOMÉTRICO PARA AVES

RESUMO – E importante uma determinação de um expoente alométrico adequado que considere o crescimento, a maturidade e o status produtivo das aves, e represente melhor o seu tamanho metabólico é importante para expressar de uma forma mais acurada as exigências de energia liquida de mantença para aves em crescimento, aves adultas produtivas e não produtivas. Um estudo de meta analises foi conduzido com o objetivo de estabelecer o coeficiente alométrico para aves de diferentes categorias (aves em crescimento, adultas produtivas e não produtivas), e estimar a energia liquida de mantença. Com esse intuito, um total de 124 dados (produção de calor no jejum, peso corporal, idade, ano de publicação e temperatura), foram analisados tanto na qualidade dos dados quanto nos procedimentos estatísticos de valores influentes e valores atípicos. A agrupação dos dados foi realizada de acordo com a categoria e conferidas pelo analises de clusters. O procedimento do analises dos dados individuais para ajustar o modelo ($a \times BW^b$) foram feitos considerando pelo efeito ponderado de cada estudo pelo procedimento estadístico PROC MIXED do programa estatístico SAS. Foi observado diferencia estadística das categorias avaliadas com o cálculo de um expoente único, e significativamente diferente com o 0.75 tipicamente utilizada. A ELm diferiu entre as categorias obtendo-se valores de 470, 341, 308 kJ por quilo de peso metabólico para aves em crescimento, galinhas de produção e galos adultos, respetivamente. Utilizar apenas um exponente não é recomendado, decorrente do ajuste de todas as espécies podendo subestimar as exigências de ELm, sendo viável usar a média obtida entre todas as categorias.

Palabras-chave: Taxa metabólica basal, Produção de calor no jejum, Aves em crescimento, Aves adultas

NET ENERGY FOR MAINTENANCE AND ALLOMETRIC EXPONENT FOR POULTRY

ABSTRACT – It is important to determine an adequate exponent that considers the growth, maturity and the productive status in poultry and has a better representation of metabolic size, to have a more accurate expression of the net energy requirements for growth, adult productive and adult non-productive birds. This study was performed to establish the allometric coefficient of different birds' categories (growth birds, adult productive and non-productive birds), and estimate the net energy to maintenance. A total of 124 data (fasting heat production, body weight, age, year of publication and temperature) was submitted to several quality and statistical analyses of outlier and leverage points. The criterium to classify the date per category was performed by the cluster analyses. The model $a \times BW^b$ was fitted using individual data, in which the effect of each study was weighted using PROC MIXED procedure of SAS statistical software. The allometric exponent between categories not differ (P>X.XX), while statistical difference was observed between when a single exponent was calculated with all data base and 0.75 was tested. The NEm between categories, where 470, 341, and 308 kJ per metabolic weight per day, to growing chicks, laying hens and cockerels, respectively. A single allometric exponent fitted for all category is not recommended, since it could sub-estimate the NEm requirement, thus, an average of allometric exponent obtained from each category should be used.

Keywords: Basal Metabolic Rate, Fasting Heat Production, Growth Birds, Adult Birds

CHAPTER I – GENERAL CONSIDERATIONS

INTRODUCTION

The energy metabolism in complex organism is based on a nutrient and their broken chemical bonding by enzymatic reaction, resulting in an oxidative reaction that releases ATP and heat (Ferrell and Oltjen, 2008). The ATP is a principal component used as an energy source for metabolic process that occur on the cells (Salin et al., 2015). The ATP measurement is difficult as a result of the hight dynamism on metabolism, for that reason the heat measurements is more suitable, based on the first law of the thermodynamic is possible to quantify the energy utilization in animals (Ferrel and Oltjen, 2008; Nienaber et al., 2009; Ballesteron et al., 2018). Extensive research was developed to study the energy metabolism, and increased with the utilization of indirect calorimetry method (Gerrits and Labussiere, 2015), based in the stichometry relation of oxidative reaction, a good indirect indicator of metabolism to explain what nutrient is currently metabolized (Table 1).

Table 1. Gaseous exchange and heat production of oxidized substances.

Nutrient	O_2 consumed (*l*) with oxidation of 1 g	Released CO_2 (*l*) with oxidation of 1 g	Heat Production (*kJ*)	Respiratory Quotient
Starch	0.829	0.829	17.57	1.00
Fat	2.013	1.431	39.75	0.71
Protein	0.957	0.774	18.41	0.81

Source: adapted from Gerrits and Labussiere, 2015.

The procedure of heat production measurement has been studied and, to some extent standardized, but is necessary to deal with caution because it is susceptible to error in methodology or data calculation (Balnave, 1974). The mean limitation in heat production and energy utilization measurements is to express both using one scale, which enables the comparison between organism with different sizes, and expressing their energy expenditure according to an effective metabolic active tissue. The basal metabolic rate (BMR) is related to the metabolic body size (MBW), based on the concept that a constant value of BMR per unit of MBW for the different size of animals in standard conditions (Johnson and Farrel, 1985).

The expression of metabolic body weight in different genotypes is questioned, and its necessary more studies to evaluate a representative value that express the energy expenditure in different categories of poultry.

OBJETIVES

To describe the allometric exponent for different poultry categories.

Elucidate about the difference to express the body size applying the allometric exponent of 0.75 and the exponent obtained by a meta-analyses for poultry.

Determine the net energy for maintenance for poultry.

LITERATURE REVIEW

Metabolic rate

The metabolic rate is defined as a metabolic activity of cells, tissues, organs and systems, all together have an energy expenditure as heat from an exothermic reaction, with a high variability, because is a result of different conditions such as the chemical and physical diet characteristics, the environment effect and health status (Richards 1977) (Figure 1). The metabolic rate in animals are expressed in different units of energy (joules, calories, etc.) per unit of time (minutes, hours, days, etc.). Many terms are described to express the metabolic rate: Basal Metabolic Rate, Resting Metabolic Rate and Starving Metabolic Rate (Rucker, 2007; Hudson et al., 2013; Bueno and Lopez-Urrutia, 2014); each one is used with specific objectives, however, the BMR is more related to the metabolic body size (BW^b) of the animals and it is used to compare the metabolism between taxonomic group and genotypes (Hudson et al., 2013).

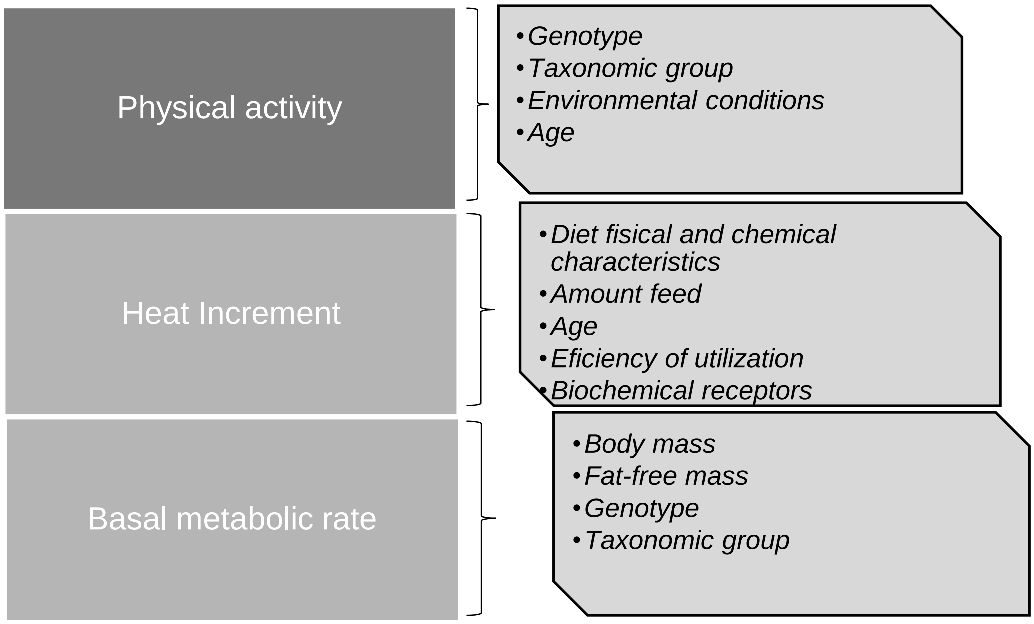

Figure 1. Partitioning of energy utilization and intrinsic and extrinsic factors that affect each components energy expenditure (source: Autor)

Basal Metabolic Rate

The basal metabolic rate (BMR) is defined, for endothermic animals, as the minimum metabolic activity during normothermia (McKechnie and Wolf, 2003; White and Seymour, 2005; Labussière et al., 2008; Genoud et al., 2018). Also, can be defined as the energy cost to maintain the thermodynamics and prioritize the homeostatic equilibrium which purpose is to maintain the life (Balnave, 1974; Galgani and Ravussin, 2008). This mechanism keeps the constant flow of nutrient sources (expressed as energy) for the circulation, excretion, secretion, respiration activities, and maintenance of muscle tone (Cramton and Harris., 1969; Kil et al., 2013). The BMR expression ($a \times BW^b$), is typically used to unicellular and complex organism, animals, populations and ecosystems. Generally, a constant value of 0.75 it is considered as the allometric scaling for adult animals (Kleiber, 1932), which could be used in adult endothermic animals, at maturity or with minimum growth (Poczopko, 1979), assuming standard conditions; nevertheless in growing animals, this power is questioned (Noblet et al., 2015).

Resting Metabolic Rate

The resting metabolic rate (RMR) it is a term used to describe the minimum metabolism under the variation of different conditions such temperature, circadian cycle, seasonality, and other factors that can influence the BMR (Berman and Snapir, 1965; Dietz and Drent, 1997; Hudson et al., 2013), but without considering the effects of metabolism from the feeding process, for that, the RMR should be measured on animals under fasting condition. In RMR measurements, the post-absorptive state is not always guaranteed and it is difficult to exclude the physical activity effect on the heat production measurement. For that reason, a respiratory quotient (RQ) close to 0.7 it is not obtained for all cases, in consequence, other criteria should be taken into consideration to establish the plateau of the minimum metabolic rate (Everts, 2015).

Net Energy for maintenance and fasting heat production

The net energy for maintenance (NEm) is the “true” energy required to maintain the life process of complex organisms, under any metabolic process not related to feeding and not affected by diet characteristics. The expression ($a \times BW^b$), should have the capacity to describe, leastwise “partially”, the flow of nutrients in a specific metabolic condition nominated as fasting heat production (FHP) (Crampton and Harris 1969; Everts 2015; Noblet et al., 2015), many authors use FHP as an indicator of NEm (Johnson and Farrel, 1985; Noblet et al., 2015; Rivera-Torres et al, 2010). In this respect, the FHP, with proper standardization to each animal species and sizes, adequate methodology, a correct statistical tool, and supported by RQ value, can be adjusted to more representative BMR value.

The methodology determine the NEm based on the gradual levels feeding and the zero-feed intake extrapolation has been criticized because this a methodology requires several assumptions (Labussière et al., 2008; Noblet et al., 2015).

Challenge to NEm measurement

Some considerations were proposed to measure the BMR in animal assay, in different conditions as the resting state, post-absorptive, non-growing and non-productive phase; but are not universally consensus (McKechnie and Wolf, 2003). However, there are some concern about NEm determination in farm animals, thus it is necessary to consider for different body size and productive status, even in adult and growing animals (Jhonson and Farrel, 1985). The FHP has been a better measurement of the BMR, supported by important biological bases, although the mathematical and statistical procedure to obtain the metabolic size function is empirical (Kleiber, 1932). The most important biological base is referred to a RQ according to the stoichiometry of oxidation of any macro nutrient (Table 1), that occurs after a considerable time during the fasting period, when the catabolism and oxidation rate of body lipids is predominant compared to the anabolism or catabolism of proteins and carbohydrates, with a value close to 0.7 (Guerrits and Labussière, 2015). To measure the FHP in growing animals, is necessary to consider some points: (1) The body weight of a fasting animal decrease animal in fasting period decrease gradually the body weight along the feed deprivation time, because its empty gut content, and the body tissue mobilization. It is questionable how and when is better to measure the correct body weight and how it can be translated to the situation of a normally growing animal. Besides it, the increase of the storage tissue catabolism and loss weight, is an unrealistic situation in growing birds (Everts, 2015). (2) The fasting time in birds, in average 24 hours (Noblet et al., 2015), may be necessary to reach the plateau in FHP, but in post-hatching or baby chicken birds is debated about the required time of fasting. (3) The physical activity is subject to a “normal” behavior, and can be disturbed for the feed deprivation, unreflecting a physical activity and can affect the FHP value. Indeed, FHP can increase in the absence of voluntary muscular activity, as an effect of environmental stimulus (Hoar, 1966) nominated as “summit metabolism”, which is the highest metabolic rate attainable at normal body temperature without voluntary muscle activity. Another point to be considered is the BMR measurement in standard conditions is not uniform for all individuals within a same species, that inhere variation is attributed to experimental error.

Controversy in allometric scaling

There is an uncertainty about the relationship between the BMR and body size, and its expression as an allometric scaling (Johnson and Farrell, 1985). The main concern is focused in the ***b*** value, and it is in fact different between species, genotypes and taxonomic group in mammals and birds (Agutter and Wheatley, 2004), as a result of evolution, adaptation and ecosystem effect (McNab, 1997;

McNab, 2009; Frasier, 2015, Noblet et al., 2015). In case of poultry, that is induced by the breeder improvement and genetic divergent. The allometric scaling is significantly heterogeneity in birds, attributed to taxonomic level and genotype varying between 0.54 to 0.95 (Hudson et al., 2013).

The proposed FHP to indicate the BMR is not completely accepted for many researchers, because the fasting state does not have a standard measurement procedure and is subject to many factors of variation such as time of fasting, previous fed level, physiological state of animals, environmental temperature, circadian cycle, etc. (Macleod et al., 1984; Macleod et al., 1985; Macleod et al., 1988; Macleod et al., 1993; Labussière et al., 2011; Ning et al., 2013).

Allometric coefficient and net energy for maintenance in poultry

Metabolic size (BW^b) is a fundamental property to express the minimum nutrient and energy requirements (Hudson et al., 2013; Noblet et al., 2015) since that the BMR is considered the baseline of the metabolic process (McKechnie and Wolf, 2003). This nutrient requirement would be expressed on a common scale of body size and making it feasible to establish comparisons in animals with different sizes, with physiological and nutritional proposes. In this context, the metabolic size cold be used to express nutrient intake (fuel), and their utilization (flow).

In poultry, body tissue gain as a meat, and consequently growth rate have several changes through years, it is result of genetic improve, but the energy cost per unit of metabolic active tissue does not change, it means that the net energy requirement (NEm) of one single metabolic active cell is constant (Glazier, 2015) because it is associated with the specific activity of enzyme-protein tissue (major metabolic component of the cell, genetic materials, enzymes, structures and hormones) called as a bio-molecular controllers of nutrient flow.

Growth versus adult poultry

The basal metabolic rate (BMR) has a close relationship with growth rate (Dietz et al., 1997), however, some authors describe that the maintenance cost is unaffected by growth rate (Ricklet., 1983), this idea has been refuted by Dietz et al. (1997), Jhonson and Farrell (1985), and Konarzewski et al. (2000), who demonstrated a difference between mature and immature birds in the allometric scaling, they attributed this discordance to a strongly positive correlation between the growth cost (growth rate) and BMR, and is possible that the BMR as a function of the body mass is not a simple allometric linear regression. Extrapolating to adult birds, this variation in BMR is minimum and it is related to a minimum growth rate. For that reason, the physiological comparison between different species have been doing in adult animals, with minimum growth (Kleiber, 1932). All of this has been explained with biological basis of the sub-system of energy flow as the heat increment (HI), growth (energy allocation or bio-syntheses), BMR (Labussière et al., 2008; Noble et al., 2015) obtained from nutrients utilization and expressed in energy terms, is a complex system, and the interaction between the components (BMR, growth and HI) is inherent and inevitable, considering each sub-systems is inside of a big close system (for this case is the bird). Unfortunately, physiological basis and experimental demonstration are not full known. Some researchers have studied this subject in different visceral size, and between growing and adult animals (Dietz and Drent, 1997). Holliday et al (1967) refers that increase of metabolic body size is parallel to the visceral size (Tess et al., 1984; van Milgen et al., 1998; van Milgen and Noblet, 1999, Konarzewsku et al., 2000), and it is better explained than by body size or surface area. This phenomenon is subject to genotype variations and between growth and mature animals (Holliday et al., 1967). The last case was better studied in infant humans where BMR per kilogram is twice than adults (Rucker, 2007). For example, Konarzewski et al., (2000) proposed that birds with similar body size changing in metabolism for three main situations: (1) A negative relationship between growth rate and BMR would be a result of the high demand of the growth process, that must be covered at the expense of the cost of maintenance. This is a principle of the energy partitioning. For example, laying hens have lower growth velocity than broiler chicks as a result of divergent genetic, that can be resulting in a different BMR. (2) No relationship suggest that independent of the growth rate of birds, the BMR is the same because the metabolic machinery activity is similar for process the feed and use nutrient. The feed process capacity, different nutrient utilization, digestibility, gut capacity, digestion time, and energy allocation efficiency, expressed in a same scale are close in laying hens and broiler chicks. (3) A positive relationship can be due to that the determination of growth rate that may lie in the proportion of immature tissues capable of growth and their high energy demand, as opposed to those that mature tissue that has a minimum energy cost to metabolic activity. It is necessary to clarify that the average of tissue deposited as energy is a result of total metabolism, the feed energy available, and growth efficiency. This components were changing thought years as a principal objective of genetic advance, moduling the nutrient utilization (Dietz and Drent, 1997), a different issue than in the BMR, that could be a consequence. For the mentioned, is necessary to study the BMR in different age, productive status, and genetics of poultry.

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CHAPTER 2 - Allometric Scaling, Metabolic Body Size and Net Energy Requirement for Maintenance: A Meta-Analyses Approach

This chapter is presented according to guidelines of Journal animal

Allometric Scaling, Metabolic Body Size, and Net Energy Requirement for Maintenance: A Meta-Analyses Approach

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Abstract

The basal metabolic rate would be express as NEm in poultry and can be measured by FHP in standard conditions. The difference between ages, growth, adult, or productive status may leads to difference of allometric exponent, as well as in NEm. A substantial amount of quality data is required to estimate the allometric exponent and determinate the NEm to each category of poultry. A meta-analyses (n=124) was performed to estimate the allometric exponent and determinate the NEm for growth, productive adult and non-productive birds. Several statistical analyses were carried out (outlies and influence point), the correlation and multiple regression analyses to identify factors that affect the BMR, and the clusters analyses was performed to define the categories. The qualitative and quantitative analyses was performed by typical meta-analysis procedure to extract data, and to determine the BMR by mixed models procedure. Was described three models considering the body weight effect (Model 1), interactions body weight and age (Model 2) and fixing the typicall allometric exponent (0.75). To the Model 1, the results revealed differences ($P<0.001$) in the allometric exponent between each categorie: growth chicks (0.72±0.013), adult productive (0.69±0.025), and adults (0.67±0.020); from a single exponent for poultry in general of 0.61±0.007 (*Gallus gallus*). The Model 2 was just described to Gallus gallus and growing categories. On the other hand, was observed slightly hight error when was used the exponent 0.75 for all cathegories, that suggest that Model 3 superstimated the NEm in poultry birds. The NEm differed between poultry categories ($P<0.001$), thus NEm was 471, 340, 305 kJ per kilo of metabolic body weight per day to growth chicks, laying hens and cockerels, respectively. Is recommended a average of allometric exponent 0.70 for practical application to express the metabolic size with different NEm values to each category, different of 0.75.

Keywords: Basal metabolism, Fasting heat production, Growth chicks, Adult birds, Allometric exponent

Implications

Net energy for maintenance (NEm) to each This study proposed to demonstrate that the typical exponent of 0.75 used to express the metabolic size of poultry does not reflect the allometry of basal energy expenditure, also is not constant in different categories concerning the growth, maturity, and productive status of the bird. The application of a high allometric exponent can over-estimate the requirement of energy and other nutrients. The allometric exponent differs between poultry categories. Thus, it could be more adequated to use an exponent that represents the species category compared with reported in the literature.

Introduction

Metabolic rate is defined as the metabolic activity of the cells expressed in terms of energy expenditure from the oxidation of nutrients in a specific time (McLean and Tobini, 1988). For endothermic animals, the rate at which an individual produces heat during a resting state in normothermia is defined as the basal metabolic rate (BMR) (McKechnie and Wolf, 2004; White and Seymour, 2005; Labussière et al., 2008; Genoud et al., 2018), its energy demand is necessary to keep the homeostatic equilibrium to maintain the life (Balnave, 1974; Bellesteros et al., 2018; Galgani and Ravussin, 2008). In the same way, the net energy for maintenance (NEm) is the amount of energy to maintain process essential to life before an extra deposition of tissue, or any products can be turned out and is an introduced term to describe the basal energy utilization in studies of animal nutrition (Armsby, 1912; Armsby and Friez, 1915). The NEm can be described from a specific metabolic state, through the measurement of the energy expenditure in standard conditions without feeding process effect, during the stable fasting period, known as fasting heat production (FHP) (Crampton and Harris 1969, Everst 2015; Noblet et al., 2015). The FHP measurement procedure is a useful methodology for poultry trials and is supported by a biological meaning as the respiratory quotient close to 0.7, according to the stoichiometry of lipid oxidation (Mellen and Hill, 1955), that gives an idea about how much energy is drawing from body energy storage, principally of lipid tissue. Additionally, When the QR is close to 0.70, this means that the animal has used most of its glycogen reserves. Also, the animal has probably reduced its energy expenditure (include of the GI-tract) to “save” energy. The longer the animals are fasting, the lower the FHP probably will be. Therefore, the length of the fasting period also affects the estimate. We can assume that the BMR is essentially an ATP requirement to keep vital functions going. The cost to produce 1 ATP is approximately the same for lipid and glucose, but it will be higher for (catabolized) body protein. Although, the statistical procedure to obtain the metabolic size function ($\boldsymbol{a} \times BW^{\boldsymbol{b}}$) is empirical (Bennet 1988; Spaargaren, 1994; Oltjen et al., 2013), where can be obtained the NEm requirement (*a*) per unit of metabolic size ($BW^{\boldsymbol{b}}$). Also, the metabolic size is a fundamental property to quantify and express the basal essential nutrient and energy requirements of animals, as the determination of the metabolically active fraction of the body (Rucker 2007; Hudson et al., 2013; Noblet et al., 2015), since the BMR is considering as the baseline of metabolic parameters (McKechnie and Wolf, 2004), with the aim to comparison within species and intraspecies, with physiological and nutritional purposes.

Some considerations were necessary to measure the BMR in animal assays, as the resting, post-absorptive, non-growing and non-productive state (Ricklefs et al., 1996; McKechnie and Wolf, 2004), with several limitations to estimate the NEm for farm animals, since it is necessary to have that values for different mass, ages and productive status, including adult and growth animals within of each species (Jhonson and Farrel, 1985). The relationship of BMR and the body size is uncertainly (Johnson and Farrell, 1985). The main controversy is focused on allometric coeficien (*b* value), which describe the metabolic weight, and it is, in fact, variable between age, physiological status, genotypes, and taxonomic group in birds (Donhoffer, 1986; Agutter and Wheatley, 2004; Hudson et al., 2013), even when many authors consider the allometric scaling *b* as a constant value of 0.75 (Kleiber, 1932). While this value was obtained in adult endothermic animals (from different species), at maturity or with minimum growth (Poczopko, 1979), for small or/and growth animals, its power is questioned (Noblet et al., 2015). In this context, allometric scales such as 2/3 and 3/4 were proposed, being the most commonly used (Hudson et al., 2013). The 2/3 exponent is supported by surface area law (Rubner, 1883) which relate the surface area and volume, clearly explain from the energy transference theory (Kleiber, 1961). The principal limitation to demonstrated the accuracy the power of 2/3 allometric exponent is the measure of the animal surface area, and it was considered all animals as a geometric solid (e.g. cube), but it does not represent the real spatial form of all species of animals, in consequence with impresicion in heat tranfer estimation per unit of surfice area. Even if it has a better fit to larger animals, this does not occur for small animals. On the other hand, the 3/4 was proposed by Kleiber (1932) using the indirectly heat production from the gas exchange, and empirically adjusting it, but with a lack of biological, physical and mathematical bases (Glazier, 2005). Even so, Kleiber's theory is more commonly used for poultry birds. Therefore, this meta-analysis was conducted to described the allometric exponent with the relationship between the body weight and fasting heat production, and to estimate the net energy for maintenance in poultry birds.

Material and methods

Search, Systematization and Data Collection

Were include peer-reviewed papers and literature published between 1970 and 2019 in a quantitative meta-analysis. All these publications were searched in available databases (Google Scholar, Web of Science and Scopus) using the keywords: heat production, energy metabolism, energy expenditure, gas exchange, fasting heat production, metabolic rate in poultry. Besides, was consulted extra literature by cross-reference. To be included in the final database were considered studies that had used indirect calorimetry to measure fasting heat production and energy metabolism. A total of 24 studies were selected, were carried considering that they in one of the following categories: growth chicks, productive adult birds (laying hens), and non-productive adult birds (cockerels). General information was extracted from the materials and methods section of each study as the sample size (n), age (days), indirect calorimetry used method (open or close-circuit), recorded environmental temperature (T) and the duration of fasting period (hours). On the results section, was extracted another group of quantitative data as the body weight (BW, kg/bird), daily gas exchange parameters (oxygen consumption, L/bird - VO2 and dioxide of carbon production, L/bird - VCO2), respiratory quotient (RQ), and the heat production (HP, kJ/bird.d). In some papers that did not report the HP, it was calculated by Bronwer (1985) equation: $\mathrm{HP}\ (kJ/bird.d) = 16.18 \times \mathrm{VO_2}(L/bird) + 5.02 \times \mathrm{VCO_2}(L/bird)$. Was used the RQ close to 0.7 with the objective to establish the fasting state for subsequent analysis.

Selection and Analysis of the Data

The literature information was analyzed individually and evaluated their quality and relevance to the objective of the meta-analysis (Sauvant et al., 2008). Treatments or conditions where was evaluated metabolic alterations or were reported a positive or negative significant change on the metabolism, like health challenges, temperature variation, or any induction of specific physiological response not was considered, only was used the naive control treatments. Particular attention was given to the meta-design to determine the better relationship between the independent variables that could affect the response variable. For that was analyzed the clusterizing, correlation degree, the weighted by multiple regression, and collinearity analysis.

Cluster Perform for the Categories Defining

Was used the categorical k-means clustering analysis to define the correspondence between poultry categories previously described in each study (growth chicks, laying hens, and cockerels), according to the observed variables of the BW, Age, and FHP. For that was applied the distance from the centroid with the squared Euclidian method, using the PROC FASTCLUS procedure of SAS (SAS Institute Inc., Cary, NC, USA).

Graphical and Multiple Regression Analysis

Was presented a graphical analysis to observe the distribution and obtain a general view of data consistency and heterogeneity. Based on this analysis, were formulated correlation hypotheses to define the interaction between variables by Pearson matrixial correlation between FHP, Age, BW, and T, using the PROC CORR procedure of SAS (SAS Institute Inc., Cary, NC, USA). Were performing a multiple regression analysis to determine the weight of each independent factor (Age, BW, and T) on the FHP by using a PROC REG procedure of SAS sofware (SAS Institute Inc., Cary, NC, USA).

Mixed Model Analyses

The tested variable in the models was the variability in the BW and their respective Age to predict the FHP. Was adjusted the data in the follows mixed model:

$$Y_{ijk} = B_0 + S_i + B_1 X_{ij.} + B_2 X_{ij.} X_{i \cdot k} + b_i X_{ijk} + \varepsilon_{ijk}$$

Where: Y_{ijk} is the FHP (in Log form); B_0 is the overall intercept; S_i is the random effect of the i^{th} study; B_1 is the overall regression coefficient; B_2 is the coefficient of the interaction of $X_{ij\cdot}$ and $X_{i\cdot k}$; $X_{ij\cdot}$ is BW (Log form); $X_{i\cdot k}$ is Age (Log form); b_i is the random effect of i^{th} study on the regression coefficient of *Y* on *X*, and ε_{ijk} is the residual errors ~N(0, SD^2); ε_{ijk}, *S* and S_i are assumed to be independent random variables. Were proposed three variants of the model: Model 1 using the BW as only predictor variable that describes the FHP (B_2 = 0); the Model 2 considering the Age×BW interaction that describes the adjustment of the allometric exponent, and the Model 3 was set to obtain the B_0, fixing the commonly allometric exponent (B_1 = 0.75) and without the age effect (B_2 = 0). The models were fit to each category (Growing, Adult productive and Adult non-productive birds). Also, was fit to the data grouping Adul birds (considering Adult productive and Adult non-productive birds together) and *Gallus gallus* (all data unconsidering the categories).The data was extracted using the PROC MIXED procedure considering the studies as a random effect (Sauvant et al., 2008).

General models fit comparison will be analyzed according to the root mean standard of error (RMSE), information criterion of Akaike (AIC) and Bayesian (BIC). Where for all criteria, a low value indicated better fit of the model. Also, it was plotted the observed versus predicted by each model to describe the slope and determine their sub estimation or overestimation. The coefficient inter categories of the Model 1 and Model 2, was compared using a categorical predictor and their interaction with a $P<0.05$. Additionally, it was analyzed the collinearity between parameters predicted for the bird categories by the variance inflation factor (VIF), where VIF>10 indicated serious collinearity.

Allometry description of avian species

Finally, was doing a collection data about different allometric exponent proposed for avian species (Table 6), and compared with that were obtained in this study to observed their distribution with a 95% of confidence interval.

Results

Data analysis selection

The search of literature resulted in a total of 29 (*n* = 219) studies on energy metabolism and gas exchange measurement in poultry, potentially suitable for meta-analysis. After the critical analyses (quality, graphical, and statistical analyses of outlier and influence points), the data was reduced to 24 studies, with a sample size (n) of 47, 52 and 25 for growing birds, adult productive, and adult non-productive; respectively (Table 1).

Cluster analysis and determination of categories

To the cluster analysis (Figure 1), was possible to differentiate three groups, with significant representation with 91.4% of the growth chicks include on the Cluster 1, 110.7% of the laying hens on the Cluster 2, and Cluster 76% of the cockerels on the Cluster 3; each one with a high concentration of data inside of the distance between cluster centroids. It analyses was helped to establish the group of categories, that was markedly defined.

Correlation between parameters and multiple regression analysis

The Pearson analysis (Table 2) were showed a positive correlation (P<0.0001) between FHP and the BW (r=0.854) and Age (r=0.364); meanwhile was showed a negative correlation (P<0.0001) between FHP and T (r=-0.348). This suggests that exists a dependence between the evaluated factors. It is necessary to mention that the BW and Age were positively inter-correlated (r=0.569, P<0.0001) and both, negatively correlated with T (r=-0.259, P=0.0037; and r=-0.271, P=0.0023, respectively). Based on the correlation results, we can conclude that exist a dependence or interaction between independent variables (BW, Age, and T). It was elucidated with the multiple regression analyses (Table 3), considering the interaction between independent factors. From parameters determined by multiple regression, were observed the factors and their interaction effects on the FHP, being found that the BW and the interaction between BW and Age were significatively (P=0.001 and P<.001, respectively). However, just the variable Age did not have a significatively effect (P=0.075) on the response variable. On the other hand, the T and their interaction with the BW and the Age were not significatively (P=0.076, and P=0.128). Based on these results was proposed models, considering the individual effect of BW, and their interaction with the Age, to estimated the FHP and determined the allometric exponent for each category.

Mixed model analyzes

The fit parameters from mixed model to Model 1, 2, and 3 is presented at Table 4. In order to that, was obtained the follow coefficient to each cathegories for significant fit (P<0.05) models: To the *Gallus gallus* B_0=2.618 and B_1=0.612 (Model 1); B_0=2.661, B_1=0.895, and B_2=-0.178 (Model 2); and B_0=2.584 (Model 3). To the Adult B_0=2.538 and B_1=0.670 (Model 1). To the Growing B_0=2.673 and B_1=0.719 (Model 1); B_0=2.685, B_1=0.934, and B2=-0.202 (Model 2); and B_0=2.698 (Model 3). To the Adult productive B_0=2.532, and B_1=0.693 (Model 1). Finally, to the Adult non-productive birds was B_0=2.485 and B_1=0.730 (Model 1); and B_0=2.124, B_1=-3.610, and B_2=1.900 (Model 2). The mixed model description with the Model 1 was significative (P<0.001) to all categories, where were observed that the Adult non-productive birds presented a better fit (RMSE=0.059) but with hight values of AIC and BIC (-91.2, and -90.2), while the Gallus gallus (unconsidering the categorization) presented a hight RMSE

(0.099) compared with other categories, opposed to a lower AIC and BIC (-176.3 and 173.5; respectively). To the Model 2 was shown only the fit for Gallus gallus ($P<0.0001$), Growing ($P<0.0001$) and Adult non-productive ($P=0.02$) birds, where this last category obtained the lower RMSE (0.047) but a greater AIC and BIC (-84.4 and -81.2; respectively). On the other hand, Gallus gallus had the lowest AIC (-128.7) and BIC (-125.9). The description by fixing coefficient ($B_1=0.75$) described by the Model 3 was only significant to adjust to following categories: Gallus gallus ($P=0.001$) and Growing ($P=0.014$), beginning that AIC and BIC were same (307 and 99.9, respectively to each class).

Inside the coefficient comparison analyses on Model 1, it was shown that just the intercept (B_0) between Gallus gallus and Adult non-productive birds not differed ($P=0.400$); they also had collinearity (VIF=102). On the other hand, the slope (B1) of Gallus gallus and Growing birds was the only different ($P<0.0001$). For the Model 2 was found that Gallus gallus, Adult and Adult productive categories presented a different intercept ($P<0.0001$), while the Adult non-productive was highly collinear (VIF= 1377.8), also the bodyweight effect coefficient (B_1) was different between all categories ($P>0.05$), like the interaction body weight and Age (B_2), except to Adult birds ($P=0.047$). The B_1 and B_2 coefficient presented collinearity between all categories (VIF>10). On the other hand, to the comparison of Models 1 and 3 (Figure 2) was shown that the Growing ($B_1=0.719$), Adult ($B_1=0.670$) and Gallus gallus ($B_1=0.612$) presented better fit (RMSE: 0.072, 0.070, and 0.099; respectively) with the Model 1. To observed-predicted plot was showed that the slope for Growing (Model 1, 2, and 3) and *Gallus gallus* (Model 3), presented a slope close to 1. To the other models, the slope was lower than 1; this means that the models could underestimate the net energy to maintenance with a large bias.

A comparison of allometric exponents previously reported in the literature (box-plot in Figure 4), and the obtained in this study, where the categories of Growing, Adult, and Adult non-productive were very close and to the second quartile, besides, were distributed inside of the interquartile range (95% confidence interval). While, the and *Gallus gallus* was below of the first quartile, reporting a lower value for the allometric exponent of the avian species.

Discussion

About the BMR, focused as a meta-analytic approach, that in essence is the collection of data from many years, and is susceptible to questioning if the genetic advance thought years could be changed the basal energy cost of birds. For that, it is necessary to mention that extra body tissue mass gain (e.g., meat or egg) and the efficiency in energy utilization was affected by genetic improvement. Consequently, the growth rate had several improvements through years (Gous, 1981; Tavarez, 2016), but the energy cost per unit of active metabolic tissue did not change, it means that the NEm of one single metabolic active cell is constant (Rucker, 2017) because it is associated with the specific activity of enzyme-protein tissue; majority metabolic components of the cell, as genetic materials, enzymes, structures and hormones, and bio-molecular components to maintain of nutrient flow (Glazier, 2005). In the case of poultry and the difference between growth chickens, laying hens and cockerels; is referred to genotype classification, that is induced by genetic divergent improvement, principally referred to physiological changes to attending specific productive objectives. It is necessary to clarify that the average as a tissue deposited as energy is a result of total metabolism, the feed energy available, and growth efficiency since that suffered the genetic advance with a nutritional modulation (Dietz and Drent, 1997), but in principle, the energy cost to maintain the unit metabolic fraction is not affected by this nutritional adaptations. Was observed by Brody (1945), Berman and Snapir (1965), and Johnson and Farrel (1985) variation between categories, according to maturity degree, with similar tendency to mature birds (B_0=0.60) less than immature birds (B_0=0.65), and disregarding the mature degree (B_0= 0.614) was very close to obtained in the present study (*Gallus gallus*). The difference between categories is an interaction between the mass and the age, the first describes the body fraction potentially active (metabolically tissues), and the second is related with the physiological status, depending on their productive objectives that could affect the development of their metabolic processes. As was a statement by Kleiber (1961): “In many cases the metabolic effect of body size and age are superimposed, and it then becomes necessary in studying the effect of age on metabolic rate to state in what unit of body size one expresses the metabolic rate,” is challenging to isolate the effect or evidenced their interaction in the BMR in animals along with their growth and productive status, but categorizing, is possible to observe their influence, as was describer in this study, where only in growing animals, because have a large variability of mass and ages, and considering all data (*Gallus gallus*) were evidenced the interaction of body weight and age.

All obtained average allometric exponents in avian specie were less than 0.75, the main difference between allometric scaling and, as a consequence, the NEm between birds, is because the BMR has a close relationship with the growth and their physiological status (Dietz et al., 1997). Many authors affirm that maintenance cost is unaffected by growth process (Rubner, 1902 and Ricklet., 1983). However, this affirmation was rebutted by Kleiber (1961), Dietz et al. (1997), Jhonson and Farrell (1985), and Konarzewski et al. (2000), who demonstrated that exists a difference between mature and immature birds in the allometric scaling, and they attributed that discordance to a strongly positive correlation between growth, more precisely with the physiological and metabolical changes which entail the growth, and basal metabolic rate. It was same as that observed in our study. In adult birds, variation in BMR is minimum, and it is related to minimum metabolic alterations. That is the reason why the comparison, to a physiological approach, between different species can be made in adult animals, with minimum growth (Kleiber, 1932). Holliday et al. (1967) refer that increase in metabolic body weight and NEm is parallel to the visceral size and could be better explain the BMR than the body size or surface area. This phenomenon is subject to specific metabolic activity between growth and mature (Holliday et al., 1967). The allometric scaling in avian species is heterogeneous, attributed to the taxonomic group and genotype, varying between 0.54 to 0.95 (Johnson and Farrel, 1985; McNab, 2009). The allometric exponent to practical application, could not be used from all data (Gallus gallus) and neither 0.75 but would be expressed as an average of exponent founded in each category (B_0=0.70) with minimum variation, that is equal to obtained by Noblet et al. (2015).

The NEm values, per unit of metabolic weight, was very close to obtained by Sakomura et al., (2005) for laying hens (345 kJ/kg$^{0.75}$), and for the average of all categories (397 kJ/kg$^{0.75}$). On the other hand, the NEm for growing birds reported by Sakomura et al., (2005) and Noblet et al., (2015) was slightly lower (415-448 kJ/kg$^{0.75}$, and 420 kJ/kg$^{0.70}$; respectively) than found in this study, being close to Model 1 (Table 7), but with reliable differentiation between categories could be described, the same as can be obtained with the proposed models.

In conclusion, the present study, compiled data for different categories and size of poultry birds, provide strong evidence that the allometric scaling to describe the metabolic size is less than 0.75 in this species, and reported the importance of the difference between growth, adult and productive status. Recommended the allometric exponent for poultry birds as a mean of 0.70, with different values of NEm requirement of 471, 340, and 305 kJ per day for growth, productive adult, and adult non-productive birds, respectively.

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Table 1 *Description data used in this study[1].*

Item		Growing birds n = 47		Adult productive n = 52		Adult non-productive n = 25	
Age (days)	Range (max-min)	56	5	504	77	540	350
	Mean (SD)	28	13	259	115	479	78
Body Weight (kg)	Range (max-min)	3.00	0.07	3.72	1.01	5.21	2.31
	Mean (SD)	1.146	0.759	1.844	0.775	3.474	1.207
RQ	Range (max-min)	0.79	0.61	0.82	0.68	0.75	0.68
	Mean (SD)	0.73	0.04	0.74	0.04	0.74	0.01
FHP (kJ/b.d)	Range (max-min)	1122	54	971	274	1013	415
	Mean (SD)	515	244	538	195	765	202
Temperature (ºC)	Range (max-min)	32	21	25	20	25	22
	Mean (SD)	24	3	22	2	23	1

[1] Obtained from: Barzegar et al., 2019; Boshouer & Nicase, 1985; Boshouwers & Nicase, 1981; Collin et al., 2003; Farrell & Swain, 1977; Gereart et al., 1988; Jadhao et al., 1999; Johnson & Farrell, 1983; Koh & Macleod, 1999; Kuenzel & Kuenzel, 1977; Li & Ito, 1991; Liu et al., 2014; Liu et al., 2017; Macleod et al, 1993; Misson, 1974; Ning et al., 2013; Ning et al., 2014; Noblet et al., 2015; O`Neill et al., 1971; Rising et al., 1989; Tullett et al., 1980; Wu et al., 2018; Zhou & Yamamoto, 1997; Zubair and Leeson, 1994.

Table 2 *Correlation analyses of parameters evaluated (n = 124).*

	FHP	BW	Age	T
FHP	1	0.854[1]	0.364	-0.348
		<.0001[2]	<.0001	<.0001
BW		1	0.569	-0.259
			<.0001	0.0037
Age			1	-0.271
				0.0023
T				1

Age (d). Body weight (kg). Fasting heat production (kJ/b.d). Temperature (ºC). [1]Coefficient of correlation. [2]Probability.

Table 3 *Multiple regression and weighted of each independent variable (n=124).*

Variable	B_i	SE	P
B_0	446	174	0.011
X_1	551	159	0.001
X_2	-2.04	1.52	0.183
X_3	-11	6.12	0.075
X_1X_2	-0.341	0.083	0.000
X_1X_3	-12.53	6.99	0.076
X_2X_3	0.1041	0.0679	0.128
$FHP = B_0 + B_1BW + B_2Age + B_3T + B_4BW.Age + B_5BW.T + B_6Age.T + \varepsilon$			<0.0001.

B_i: coefficients (where i= 0,…, 6). SE: Standard error. P: Probability.

Table 4 *Parameters estimates for the mixed model adjusted for fasting heat production (FHP), body weight (BW), and Age for each poultry categories.*

Model	Category	Equation	P	RMSE	AIC	BIC
Model 1	*Gallus gallus*	$Y = 2.618 + 0.612X_1$	<0.0001	0.099	-176.3	-173.5
	Adult	$Y = 2.538 + 0.670X_1$	<0.0001	0.070	-114.7	-112.4
	Growing	$Y = 2.673 + 0.719X_1$	<0.0001	0.072	-104.0	-102.2
	Adult prod.	$Y = 2.532 + 0.693X_1$	<0.0001	0.074	-79.2	-77.3
	Adult non-prod.	$Y = 2.485 + 0.730X_1$	<0.0001	0.059	-91.2	-90.2
Model 2	*Gallus gallus*	$Y = 2.661 + 0.895X_1 - 0.178X_1X_2$	<0.0001	0.100	-128.7	-125.9
	Adult	$Y = 2.540 + 0.230X_1 + 0.170X_1X_2$	0.636	0.072	-115.3	-113.0
	Growing	$Y = 2.685 + 0.934X_1 - 0.202X_1X_2$	<0.0001	0.066	-94.9	-93.1
	Adult prod.	$Y = 2.536+ 0.293X_1 + 0.152X_1X_2$	0.670	0.074	-79.8	-77.9
	Adult non-prod.	$Y = 2.124 - 3.610X_1 + 1.900X_1X_2$	0.020	0.047	-84.4	-81.2
Model 3	*Gallus gallus*	$Y = 2.584 + 0.75X_1$	0.001	0.116	307.0	307.0
	Adult	$Y = 2.514 + 0.75X_1$	0.176	0.072	200.9	200.9
	Growing	$Y = 2.698 + 0.75X_1$	0.014	0.073	99.9	99.9
	Adult prod.	$Y = 2.530 + 0.75X_1$	0.327	0.072	121.3	121.3
	Adult non-prod.	$Y = 2.480 + 0.75X_1$	0.783	0.058	71.5	71.5

X_1: body weight. X_2: Age. P: Probability of the fit model. RMSE: Root mean standard of error. AIC: Akaike information criterium. BIC: Bayesian information criterium.

Table 5 *Parameters comparisson between the Model 1 and Model 2, for each categories*

Model	Term	N	B_i	SE	P	VIF
Model 1	***B_0***	124	2.618	0.007	<0.0001	
	X_1		0.612	0.015	<0.0001	2.2
	B_0					
	Adult	77	-0.079	0.020	<0.0001	4.7
	Growing	47	0.055	0.013	<0.0001	1.2
	Adult prod.	52	-0.086	0.025	0.001	5.1
	Adult non-prod.	25	-0.132	0.157	0.400	102.0
	X_1					
	Adult	77	0.058	0.044	0.189	4.9
	Growing	47	0.107	0.028	<0.0001	1.4
	Adult prod.	52	0.080	0.060	0.182	5.2
	Adult non-prod.	25	0.117	0.056	0.603	102.4
Model 2	***B_0***		2.661	0.008	<0.0001	
	X_1	124	0.895	0.034	<0.0001	14.3
	X_1X_2		-0.178	0.020	<0.0001	17.3
	B_0					
	Adult	77	-0.121	0.019	<0.0001	5.0
	Growing	47	0.024	0.013	0.058	1.6
	Adult prod.	52	-0.125	0.023	<0.0001	5.6
	Adult non-prod.	25	-0.537	0.510	0.293	1377.8
	X_1					
	Adult	77	-0.665	0.452	0.142	676.5
	Growing	47	0.039	0.079	0.624	14.9
	Adult prod.	52	-0.602	0.544	0.269	541.9
	Adult non-prod.	25	-4.500	5.890	0.445	90116.0
	X_1X_2					
	Adult	77	0.348	0.174	0.047	668.3
	Growing	47	-0.025	0.067	0.716	13.0
	Adult prod.	52	0.329	0.206	0.111	519.7
	Adult non-prod.	25	2.080	2.590	0.421	112620.2

SE: standard error. n: sample size. X_1: body weight. X_2: Age. B_0: intercept. B_1: body weight effect (slope). B_2: interaction effect between body weight and age. VIF: variance inflation factor. P: probability to hypotheses $B_i = B_j$.

Table 6 *Allometric exponent reported in the literature described to avian species (**BMR**).*

Author	BW range (kg)	Classification	*Avian sp.*
Brody and Procter, 1932	0.02 - 100	-	0.640
King and Ferner, 1961	0.001 - 10	-	0.744
Berman and Snapir, 1964	1.67 - 2.020	Laying Hens	0.610
Lasiewski and Dawson, 1967	0.001 - 0.866	Passarine	0.724
Lasiewski and Dawson, 1967	0.003 - 100	Non-passarine	0.723
Jhonson and Farrel, 1985	0.81 - 3.930	All	0.614
Jhonson and Farrel, 1985	1.55 - 3.930	Mature	0.602
Jhonson and Farrel, 1985	0.81 - 2.190	Immature	0.646
Lopez and Leeson, 2005	0.095 - 2.100	Broiler chicks	0.600
McNab, 2009	0.004 - 156	Non-passarine	0.724
McNab, 2009	0.002 - 1.259	Passarine	0.713
McNab, 2009	0.002 - 159	All	0.652
Rivera-Torres et al., 2010	0.540 - 13.770	Fast growth turkey	0.770
Hudson et al., 2013	0.003 - 156	-	0.710
Noblet et al., 2015	0.620 - 2.820	Broiler chicks	0.694
Ballesteros et al., 2018	0.005 - 9.900	Flaying bids (small birds)	0.660
Ballesteros et al., 2018	0.250 - 420	Flightless birds (incluid big bids)	0.740

BW: body weight described as was reported or was approximated from detailed in each study.

Table 7 *Net energy for maintenance (NEm) to each category compared with reported in the literature.*

Categories	Sakomura et al., 2005[1]	Noblet et al., 2015[2]	Model 1	Model 2	Model 3
Growing	415-448	420	471	484	499
Laying hens	345		340		
Adult	-		345		
Adult non-prod	-		305	-	
Gallus gallus	397		415	458	384

NEm in kJ per unit of metabolic weight described by the allometric exponent of 0.75[1] and 0.70[2].

Figure captions

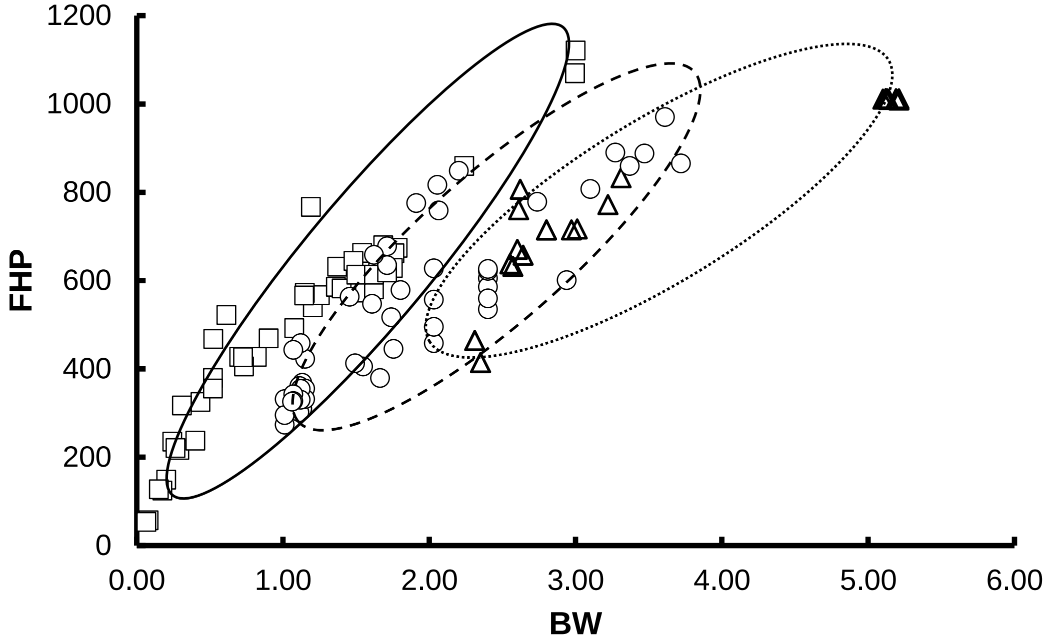

Figure 1 Clusters mapped of fasting heat production (**FHP**, kJ/b.d) and body weight (**BW**, kg) for growth chicks (□), cockerels (Δ) and laying hens (○); and clusters for Cluster 1 (observations: 43, distance from centroid: 0.497-Avg and 1.331-Max, ──), Cluster 2 (observations: 62, distance from centroid: 0.547-Avg and 1.012-Max, ----), Cluster 3 (observations: 19, distance from centroid: 0.860-Avg and 1.118-Max, ····).

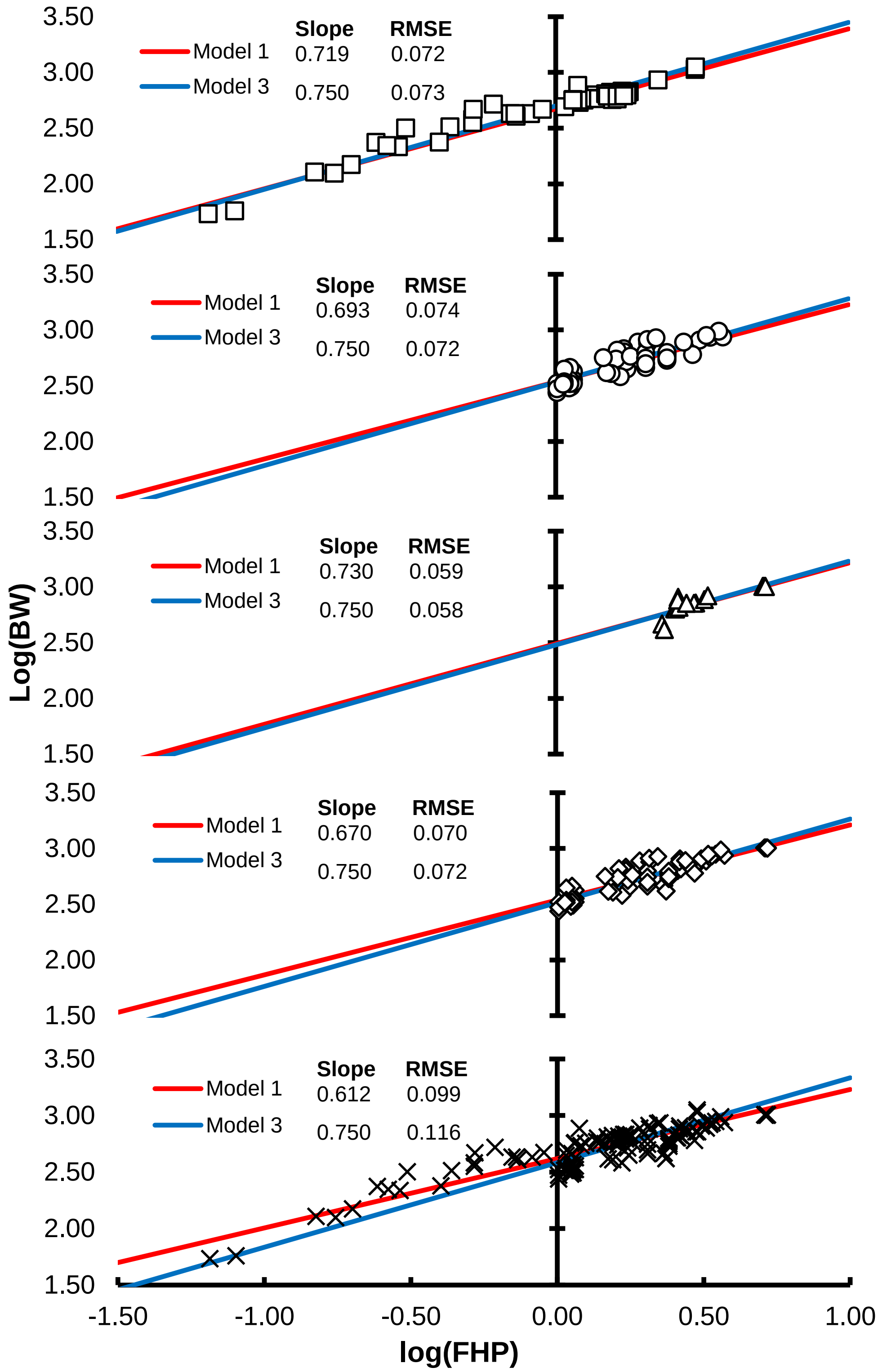

Figure 2 Observed values log-log plot of fasting heat production (FHP, kJ/b.d) and body weight (BW, kg) for growth chicks (□), cockerels (Δ), laying hens (○), adult birds (◊), and Gallus gallus (×) with respective estimated values to the Model 1 (—), and Model 3 (—).

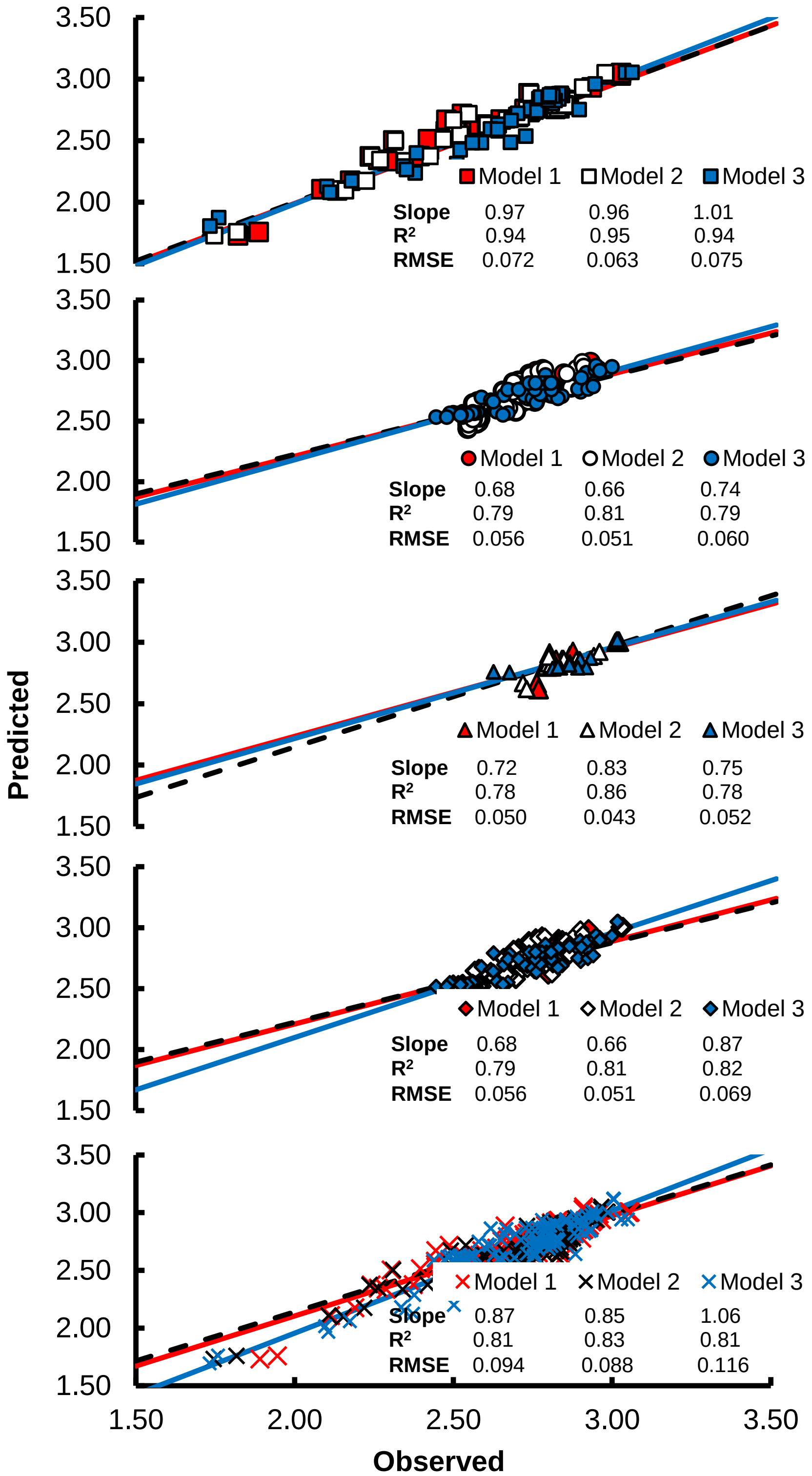

Figure 3 Observed and predicted logFHP for each models, with respective slope, regression coefficient (R^2) and the root mean square error (RMSE); for growth birds (□), adult non-productive (Δ), adult productive (○), adult birds (◊), and *Gallus gallus* (×), respectively.

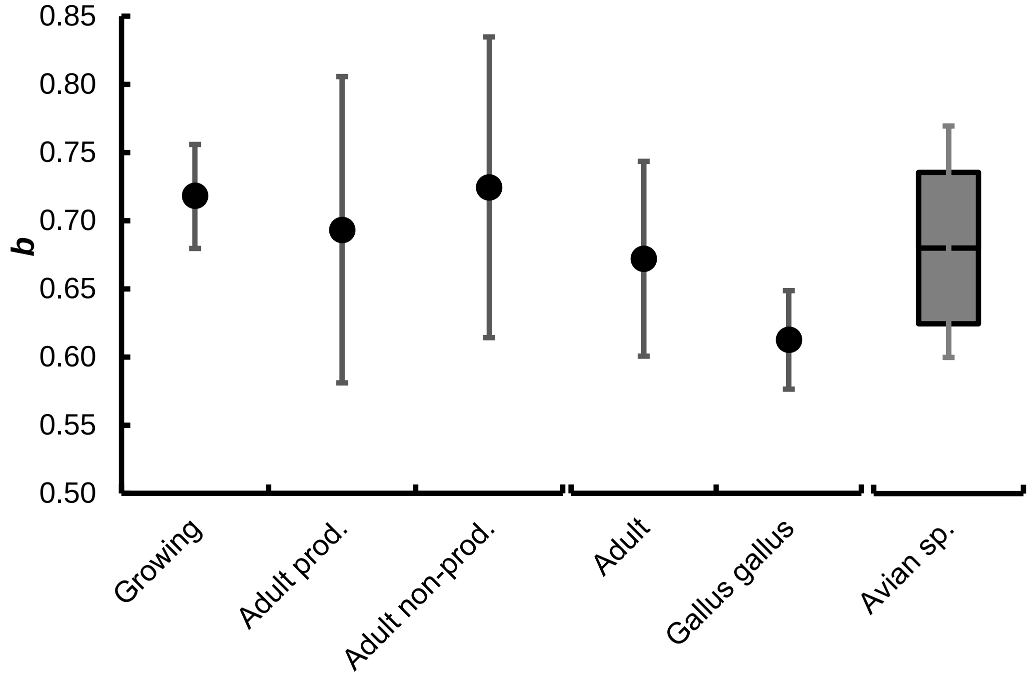

Figure 4 Box-plot of ***b*** values reported in literature to avian species and values obtained with the Model 1, with 95% of confidence of interval.