Geometrical characteristics of eggs from 3 poultry species

L. C. Wang,[*,1] Z. T. Ruan,[*,1] Z. W. Wu,[*] Q. L. Yu,[†] F. Chen,[†] X. F. Zhang,[*] F. M. Zhang,[‡] R. J. Linhardt,[‡] and Z. G. Liu[*,2]

*College of Animal Science and Technology, Zhejiang Agriculture & Forestry University, Lin'an 311300, Zhejiang, China; †Hangzhou Xiaoshan Chicken Breeding Co., Ltd., Hangzhou 311300, Zhejiang, China; and ‡Departments of Chemical and Biological Engineering, Chemistry and Chemical Biology, Biology, and Biomedical Engineering, Center for Biotechnology and Interdisciplinary Studies, Rensselaer Polytechnic Institute, Troy 12180, New York, USA

ABSTRACT We studied the correlations between egg geometrical parameters (i.e., egg shape index, sphericity, geometric mean diameter, surface area, and volume) and eggshell qualities, or the organic matrix in eggshell. Eggs were collected from 5 poultry breeds belonging to 3 species (commercial Hy-line Brown Chicken, Shaoxing Duck, Jinding Duck, Taihu Goose, and Zhedong White Goose). The geometrical parameters showed high variation among 3 species of poultry, and even between breeds in the same species. The five geometrical parameters were grouped into 2 sets, one contained shape index and sphericity, the other comprised geometric mean diameter, surface area, and volume. The parameters in the same set can be perfectly fitted to one another. Egg weight, shell membrane weight, and calcified shell weight were significantly correlated with geometric mean diameter, surface area, and volume. In accordance with false discovery rate–adjusted *P* value, both shell membrane relative weight and calcified shell thickness showed no significant correlations with any of the geometrical parameters. However, the correlations between geometrical parameters and other shell variables (calcified shell weight, shell relative weight, calcified shell thickness uniformity, and eggshell breaking strength) depend on breed. Both constitutive proportions and percentage contents of 3 eggshell matrix components (acid-insoluble, water-insoluble, and both acid and water facultative-soluble matrix) had no effects on egg shape and size. The correlations between the amounts of various shell matrix, egg shape and size depend on breed or species. This study provides a methodology and the correlation between geometrical parameters and eggshell qualities, and between geometrical parameters and organic matrix components in calcified shells.

Key words: egg, geometrical parameter, eggshell quality, eggshell matrix

2021 Poultry Science 100:100965
https://doi.org/10.1016/j.psj.2020.12.062

INTRODUCTION

The calcified eggs of birds exhibit a variety of sizes and shapes (Stoddard et al., 2017). It is a challenging task to describe egg profiles accurately because the high variability of eggs exists not only among bird species, but also among the individuals of the same flock. Precise quantification of egg profiles can provide a powerful tool for relevant biological studies on population, ecological morphology, egg incubation, and development (Barta and Szekely, 1997; Hutchinson, 2000; Stoddard et al., 2017). The knowledge of egg contours is also meaningful for the poultry industry. The egg geometrical parameters, such as egg volume, surface area, radius of curvature, etc., have been used in research on the numerical simulation of the eggshell behavior under mechanical loading (Perianu et al., 2010) or under thermal treatments (Sabliov et al., 2002; Denys et al., 2003). These geometrical parameters have also been used to predict egg qualities, breeding egg hatchability, and hatchling size (Severa et al., 2013).

Egg shape index (***SI***) is the classic geometrical parameter to describe eggshell shape (Sarica and Erensayin, 2004). In addition to *SI*, some other egg geometrical parameters and their mathematical equations have also been derived to promote the description of egg contours (Narushin, 1997). The surface area (***S***) and the geometric mean diameter of eggs (***Dg***) were given by Mohsenin (Mohsenin, 1970); based on these results, the degree of sphericity (***Φ***) and the volume (***V***) of eggs were further deduced (Severa et al., 2013).

In terms of above 5 geometrical parameters, except egg *SI*, other parameters are mainly used in the research

Received October 27, 2020.
Accepted December 21, 2020.

[1]These authors contributed equally as co-first authors.

[2]Corresponding author: liuzg007@zafu.edu.cn

of ecological morphology (Barta and Szekely, 1997; Hutchinson, 2000; Stoddard et al., 2017), and in the numerical simulation of the eggshell behavior in food processing (Sabliov et al., 2002; Denys et al., 2003; Perianu et al., 2010; Severa et al., 2013; Kumbar et al., 2016), while seldom used in research of eggshell qualities. The present study used eggs from chicken, duck, and goose to probe the correlations between geometrical parameters and eggshell qualities, and between geometrical parameters and organic matrix components in calcified shells.

MATERIALS AND METHODS

Egg Samples Collection

Eggs were collected from 5 poultry breeds of 3 species from Zhejiang Province, China (Table 1). Chicken eggs were from 280-day-old commercial Hy-line Brown Chicken cage-reared in Lin'an County. Duck eggs were from 2 breeds, the first batch was 400-day-old purebred Jinding Duck free-ranged in Yuhang County; the second batch was 450-day-old purebred Shaoxing Duck cage-reared in Zhuji County. The goose eggs were from 2 flocks: 300-day-old purebred Taihu Goose free-ranged in Nanxun County; and 320-day-old purebred, free-range Zhedong White Goose in Xiangshan County.

Eggs with normal shape and color were sampled on the laying day from each flock in the same month. The sample size of each breed was showed in Table 1.

Measurement of Egg or Eggshell Variables

Egg Weight, Length, and Width The individual egg weight was measured using balance; then egg length and width were measured using caliper.

Eggshell Broken Strength The eggshell broken strength was measured by eggshell strength gauge from Fujihara Co. (Tokyo, Japan). Each chicken and duck egg were vertically placed as sharp end head down and blunt end head up so that the blunt end bore the pressure. Goose eggs were too long to vertically place under the sensor rod, so each egg was horizontally placed to test the shell annulus with the maximum width bore the pressure.

Eggshell Membrane Weight and Calcified Shell Weight After eggshell breaking strength testing, each egg was broken into halves, the shells were washed with water, then rinsed with 5% EDTA for 30 min, 40 min, and 45 min. The cuticle covering the outer surface of calcified shell was removed using a toothbrush, then the shell membrane was carefully and manually removed from calcified shell and collected. Finally, the shell membranes and calcified shells were dried at 40°C and weighed.

Calcified Shell Thickness and Shell Thickness Integrity Using a modified method from the study by Sun et al., 2012, each calcified shell was roughly marked in 5 parts with equal length along the longitudinal axe, that is blunt end, blunt zone, equator zone, sharp zone, and sharp end. Six shell pieces were sampled around the circumference of each part. The thickness of each shell piece was measured with a digital micrometer. The average thickness of total 30 shell pieces was calculated as thickness of the eggshell. The eggshell thickness uniformity was defined as the reciprocal of the coefficient of variation (1/CV) of the thickness of 30 shell pieces of each egg. The higher eggshell thickness uniformity means more homogeneous of global eggshell thickness.

Extraction of Organic Matrix Components From Calcified Shells

Eggs from 3 breeds, Hy-line Brown Chicken, Shaoxing Duck, and Zhedong White Goose, were used for this analysis. Based on the method (Liu et al., 2017), the organic matrix components were extracted from each calcified eggshell. Briefly, the eggshell was individually powdered using mortar and pestle, then decalcified by stirring with 10% acetic acid at 20°C for about 18 h. The amount of 10% acetic acid used was about 22–25 mL per gram shell powder, and the acetic acid was added stepwise as the proportion of 35:35:30, the first 2 steps of decalcification were individually carried out over 3–4 h, and the last time decalcification was performed overnight.

After decalcification, the suspension was centrifuged (fixed-angle rotor) at 23,500 × *g* for 18 min and the pellet was washed twice with distilled water and freeze-dried and it was designated as acid-insoluble matrix (expressed as Matrix1). The supernatant (referred as acid-soluble matrix) was repeatedly dialyzed four times against 40 volumes of distilled water at 20°C using a Spectra/Por 6 dialysis tubing bag (molecular weight cutoff 8 kDa; Spectrum Labs, Rancho Dominguez, CA). The sample was then centrifuged at 3,500 × *g* for 40 min to obtain water-insoluble matrix (expressed as Matrix2) and facultative-soluble matrix (both acid and water soluble in supernatant, expressed as Matrix3). The water-insoluble matrix (Matrix2) was freeze-dried, and the facultative-soluble matrix (Matrix3) was concentrated using a Millipore spin column (molecular weight cutoff 8 kDa) and freeze-dried. The mass of each dried matrix component was individually weighed.

Calculation of Egg Geometrical Parameters

Based on the measurements of egg length ($\boldsymbol{L}$) and width ($\boldsymbol{W}$), 5 geometrical parameters were calculated:

The egg SI was calculated from the formula (Sarica and Erensayin, 2004) $SI = (W/L)*100$. The geometric mean diameter of eggs (Dg) was calculated from the formula (Mohsenin, 1970) $Dg = (L^* W^2)^{1/3}$

The surface area of eggs (S) was calculated from the formula (Mohsenin, 1970; Baryeh and Mangope, 2003) $S = \pi * Dg^2$.

In accordance with the references (Severa et al., 2013; Kumbar et al., 2016), the degree of sphericity of eggs (Φ) $= (Dg/L) * 100$; and the volume of eggs (V) $= (\pi/6) * L * W^2$.

Table 1. Five poultry breeds providing egg samples.

Poultry breeds	Age (day old)	Egg sample size	Breed characterization	Breeding site
Hy-line Chicken	280	100	commercial	Lin'an County, Zhejiang Province, China
Jinding Duck	400	71	purebred	Yuhang County, Zhejiang Province, China
Shaoxing Duck	450	97	purebred	Zhuji County, Zhejiang Province, China
Taihu Goose	300	71	purebred	Nanxun County, Zhejiang Province, China
Zhedong White Goose	320	84	purebred	Xiangshan County, Zhejiang Province, China

Statistical Analysis

The software of one-way ANOVA in SPSS 19.0 was used to analyze the difference of geometrical parameters among eggs from various flocks. The software of Bivariate Correlations in SPSS 19.0 was used to determine the strength and direction of Pearson correlation coefficients between pairs of variables, including correlations between geometrical parameters and eggshell or shell matrix variables. The classical false discovery rate–adjusted P-values were calculated using Benjamini & Hochberg methods to perform multiple hypothesis test correction (Benjamini and Hochberg, 1995). Statistical values were expressed as mean ± SD, and the threshold of significant difference chosen for all analyses was set as $P < 0.05$.

RESULTS

Geometrical Parameters of Eggs From the Five Flocks

In the present study, parameters describing egg geometrical, eggshell, and shell matrix characterizations were systematically determined (Table 2, Appendix 1 and 2). And the analysis of egg geometrical parameters (Table 2) showed: i) the differences of egg *SI* among the 3 poultry species were very significant ($P < 0.01$); ii) the difference between 2 duck breeds was also very significant ($P < 0.01$); iii) there was no significant difference between 2 goose breeds ($P > 0.05$). Egg *SI* is generally used as the geometrical parameter to describe eggshell shape. Eggs can be characterized as sharp, normal (standard), and round if they have an *SI* value of <72, between 72 and 76, and >76, respectively (Sarica and Erensayin, 2004). The *SI* of chicken eggs was greater than 76, eggs of both duck breeds were between 72 and 76, and eggs of both goose breeds were less than 72 (Table 2). This suggests that the egg shapes among these 3 species are highly variable with chicken eggs being comparatively round, goose eggs are sharp, and duck eggs have a standard shape. In addition, the sphericity (Φ) of chicken eggs was significantly larger than eggs from both duck breeds, and duck eggs were significantly larger than the eggs of both goose breeds ($P < 0.01$) (Table 2). This also shows that chicken eggs are rounder, and goose eggs are sharper.

In addition, the other 3 geometrical parameters, that is, geometric mean diameter, surface area, and volume of eggs, also showed high variation among the 3 species of poultry, and even between breeds of the same species. These 3 parameters all show that goose eggs are significantly larger than duck eggs ($P < 0.01$), and duck eggs are significantly larger than chicken eggs ($P < 0.01$) (Table 2). This is consistent with the weights of goose eggs being much larger than duck eggs, and duck eggs being larger than chicken eggs. Obviously, eggs of larger weight would also have larger contours of diameter, surface area, and volume.

Correlations Among the Five Geometrical Parameters

The results of eggs from all 5 breeds showed that the *SI* positively and significantly correlated with sphericity (adjusted $P < 0.01$) (Table 3–5). The geometric mean diameter, surface area, and volume of eggs, positively and significantly correlated with each other (adjusted $P < 0.01$) (Tables 2–4). Furthermore, the Pearson correlation coefficients ($\boldsymbol{r}$) of the above parameter pairs were all equal to or close to 1 (Tables 2–4). The squares of correlation coefficients ($\boldsymbol{r^2}$) were equal/close to 1, suggesting the parameter pairs with high correlation can be perfectly fitted by each other.

By contrast, only the *SI* or sphericity of Shaoxing Duck eggs significantly and negatively correlated with the geometric mean diameter, surface area, or the volume of eggs (adjusted $P < 0.01$) (Table 4). In the case of eggs from the other 4 breeds, there were no significant correlations between the *SI* or sphericity and the other 3 parameters ($P > 0.05$) (Tables 3–5).

Table 2. Geometrical characteristics of eggs from the 5 flocks.

Parameters	Hy-line Chicken	Jinding Duck	Shaoxing Duck	Taihu Goose	Zhedong White Goose
Shape index (%)	77.19 ± 2.35 A	73.26 ± 2.83 C	75.12 ± 2.19 B	67.75 ± 2.88 D	68.00 ± 2.22 D
Sphericity (%)	84.14 ± 1.71 A	81.26 ± 2.10 C	82.63 ± 1.61 B	77.13 ± 2.20 D	77.32 ± 1.68 D
Geometric diameter (mm)	48.37 ± 0.94 A	50.93 ± 1.20 C	50.04 ± 1.23 D	58.39 ± 1.80 B	62.77 ± 1.75 A
Surface area (cm2)	73.52 ± 2.86 E	81.52 ± 3.83 C	78.70 ± 3.87 D	107.22 ± 6.58 B	123.89 ± 6.90 A
Volume (cm3)	59.31 ± 3.47 E	69.27 ± 4.88 C	65.71 ± 4.86 D	104.54 ± 9.61 B	129.82 ± 10.80 A

Values in the same raw with same capital letters mean the difference between them is not significant ($P > 0.05$), and the different capital letters mean the difference is very significant ($P < 0.01$).

Table 3. Correlations among the 5 geometrical parameters of eggs from Hy-line Brown Chicken.

Geometrical parameters	Statistics	Shape index	Sphericity	Geometric mean diameter	Surface area	Volume
Shape index	*r*	1	1.000	−0.196	−0.197	−0.197
	P		0.000**	0.059	0.059	0.058
	Adjusted P		0.000**	0.060	0.060	0.060
Sphericity	*r*		1	−0.196	−0.196	−0.197
	P			0.060	0.059	0.059
	Adjusted P			0.060	0.060	0.060
Geometric mean diameter	*r*			1	1.000	1.000
	P				0.000**	0.000**
	Adjusted P				0.000**	0.000**
Surface area	*r*				1	1.000
	P					0.000**
	Adjusted P					0.000**
Volume	*r*					1
	P					
	Adjusted P					

**Represent the correlations between parameters were very significant ($P < 0.01$).

Based the above analysis, it seems the 5 geometrical parameters could be grouped into 2 correlated sets: 1) *SI* and sphericity; 2) geometric mean diameter, surface area, and volume, because the parameters in the same set can be perfectly fitted with each other.

Correlations Between the Geometrical Parameters and Eggshell Qualities

In terms of egg weight, shell membrane weight, and calcified shell weight, the results on the 5 breeds all positively and significantly correlated with egg geometric mean diameter, surface area, and volume (adjusted $P < 0.01$) (Table 6). Membrane weight showed no significant correlation with egg *SI* and sphericity in all 5 breeds ($P > 0.05$) (Table 6). Both shell membrane relative weight (the membrane weight normalized by egg weight) and eggshell thickness showed no significant correlation with any geometrical parameters (adjusted $P > 0.05$) (Table 6).

However, the correlations between egg weight or calcified shell weight and egg *SI* or sphericity depended on breed, that is, egg weight and calcified shell weight negatively and significantly correlated with *SI* and sphericity only in the case of Hy-line Brown Chicken and Shaoxing Duck (adjusted $P < 0.01$) (Table 6). Furthermore, the correlation between other shell variables and geometrical parameters also depends on breed. Only Hy-line Brown Chicken and Shaoxing Duck showed negative and significant correlation between shell relative weight (the calcified shell weight normalized by egg weight) with geometric mean diameter, surface area, and volume (adjusted $P < 0.01$) (Table 6), but no significant correlation with egg *SI* and sphericity ($P > 0.05$) (Table 6). In other 3 breeds, shell relative weight showed no significant correlation with all 5 geometrical parameters ($P > 0.05$) (Table 6). Calcified shell thickness uniformity of Hy-line Brown Chicken showed significant correlation with all 5 geometrical parameters (Table 6). By contrast, both duck breeds, shell thickness uniformity only positively and significantly correlated with *SI* and sphericity (adjusted $P < 0.01$) (Table 6). In both goose breeds, shell thickness uniformity showed no significant correlations with all 5 geometrical parameters ($P > 0.05$) (Table 6). Eggshell breaking strength, a very important shell trait, showed no significant correlations with all 5 geometrical parameters in the case of Hy-line Brown Chicken, both duck breeds, and Taihu Goose (adjusted $P > 0.05$) (Table 6); however, it significantly and positively correlated with geometric mean diameter, surface

Table 4. Correlations among the 5 geometrical parameters of eggs from both duck breeds.

Geometrical parameters	Statistics	Shape index	Sphericity	Geometric mean diameter	Surface area	Volume
Shape index	*r*	1	1.000	−0.320	−0.320	−0.320
	P		0.000**	0.002**	0.002**	0.002**
	Adjusted *P*		0.000**	0.002**	0.002**	0.002**
Sphericity	*r*	1.000	1	−0.321	−0.321	−0.321
	P	0.000**		0.002**	0.002**	0.002**
	Adjusted *P*	0.000**		0.002**	0.002**	0.002**
Geometric mean diameter	*r*	0.093	0.092	1	1.000	0.999
	P	0.475	0.478		0.000**	0.000**
	Adjusted *P*	0.504	0.504		0.000**	0.000**
Surface area	*r*	0.091	0.090	1.000	1	1.000
	P	0.488	0.491	0.000**		0.000**
	Adjusted *P*	0.504	0.504	0.000**		0.000**
Volume	*r*	0.088	0.087	0.999	1.000	1
	P	0.500	0.504	0.000**	0.000**	
	Adjusted P	0.504	0.504	0.000**	0.000**	

1) The upper triangular represents the results of Shaoxing Duck eggs, and the lower triangular represents the results of Jinding Duck eggs; 2) ** represents the correlations between parameters were very significant ($P < 0.01$).

Table 5. Correlations among the 5 geometrical parameters of eggs from both goose breeds.

Geometrical parameters	Statistics	Shape index	Sphericity	Geometric mean diameter	Surface area	Volume
Shape index	*r*	1	1.000	0.029	0.026	0.023
	P		0.000**	0.809	0.829	0.848
	Adjusted *P*		0.000**	0.854	0.854	0.854
Sphericity	*r*	1.000	1	0.028	0.025	0.022
	P	0.000**		0.814	0.834	0.854
	Adjusted *P*	0.000**		0.854	0.854	0.854
Geometric mean diameter	*r*	−0.183	−0.182	1	1.000	0.999
	P	0.145	0.147		0.000**	0.000**
	Adjusted *P*	0.155	0.155		0.000**	0.000**
Surface area	*r*	−0.181	−0.180	1.000	1	1.000
	P	0.148	0.151	0.000**		0.000**
	Adjusted *P*	0.155	0.155	0.000**		0.000**
Volume	*r*	−0.180	−0.179	0.999	1.000	1
	P	0.152	0.155	0.000**	0.000**	
	Adjusted *P*	0.155	0.155	0.000**	0.000**	

1) The upper triangular represented the results of Zhedong White Goose eggs, and the lower triangular represented the results of Taihu Goose eggs. 2) ** Represents the correlations between parameters were very significant ($P < 0.01$).

area, and volume in Zhedong White Goose (adjusted $P < 0.05$) (Table 6).

Correlations Between the Geometrical Parameters and Eggshell Organic Matrix

The calcified shell is a predominant contributor to the mechanical properties of eggshell, and comprised about 95% of $CaCO_3$ calcite crystals and organic matrix. Because this was the first time the correlations between the geometrical parameters and eggshell organic matrix were probed, we systemically studied the amounts of various matrix: Matrix1, acid-insoluble matrix; Matrix2: water-insoluble matrix; Matrix3: acid and water facultative-soluble matrix; and total matrix: extracted from individual calcified shell. The analysis also included the percentage contents of various matrices in per gram of shell, and the constitutive proportions of 3 matrix fractions in the total matrix. We used 3 breeds (Hy-line Brown Chicken, Shaoxing Duck, and Zhedong White Goose) for these analyses.

The results of all 3 breeds showed that the constitutive proportions of 3 matrix fractions, or the percentage contents of the 3 matrix fractions had no significant correlations with the 5 geometrical parameters ($P > 0.05$) (Table 7). Only in Hy-line Brown Chicken, the percentage content of total matrix was positively and significantly correlated with geometric mean diameter, surface area, and volume (adjusted $P < 0.05$) (Table 7). These results suggest that both constitutive proportions and percentage contents of the 3 matrix fractions had no effect on egg shape and size. In Hy-line Brown Chicken and Zhedong White Goose, the amounts of 3 matrix and total matrix in an individual eggshell were all significantly and positively correlated with 5 geometrical parameters (adjusted $P < 0.05$) (Table 7). However, the amount of any matrix in duck shell showed no significant correlation with the 5 geometrical parameters ($P > 0.05$) (Table 7). These data indicate that the correlations between the amount of matrix in an individual eggshell and egg shape and size depend on breed or species.

DISCUSSION

The precise determination of egg geometrical parameters is critical for the construction of the correct mathematical model needed for egg processing, manipulation, transport applications, and predictions in poultry production (Severa et al., 2013). A number of researchers deduced mathematical equations to express the contours of individual eggs (Narushin, 1997). The mathematical equations, of the current 5 egg geometrical parameters, are all adequately defined by only 2 variables: maximum length and width of an egg. Because the determination of egg length and width is much easier than the comparison of geometrical parameters, these equations would be very helpful for the evaluation of egg shape and size.

It has been reported that there are very significant correlations between chicken egg surface area and volume, but there is no significant dependence of both parameters on egg *SI* (Severa et al., 2013). Similarly, in the present study, eggs from 5 breeds belonging to 3 poultry species, all showed that the 5 geometrical parameters could be grouped into 2 correlated sets, one contained egg *SI* and sphericity, and the other contained geometric mean diameter, surface area, and volume. The parameters belonging to the same set can be perfectly fitted by each other with very high degree of correlation. However, except for Shaoxing Duck eggs, eggs of other 4 breeds showed that parameters in one set showed no significant correlations with parameters in another set (Tables 2–4).

Based on broad taxonomic scales of 1,400 bird species, it has been reported that avian egg shape correlated with flight ability, and adaptation for flight may have been critical drivers of egg-shape variation in birds (Stoddard et al., 2017). It is known that the wild ancestors of chicken, duck, and goose are *Gallus gallus*, *Anas platyrhynchos* or *Anas poecilorhyncha*, and *Anser cygnoides* or *Anser anser*, respectively. The phylogenetic relationship between duck and goose is much closer. In the present study, the egg geometrical parameters showed large variations among species; however, the egg geometrical parameters of both duck breeds were

Table 6. Correlations between egg geometrical parameters and shell qualities of 5 breeds.

Breeds	Geometrical parameters	Statistics	Egg weight	Membrane weight	Membrane relative weight	Eggshell weight	Eggshell relative weight	Eggshell thickness	Shell thickness uniformity	Shell strength
Hy-line Brown Chicken	Shape index	*r*	−0.218	−0.099	−0.049	−0.249	−0.083	−0.082	0.317	0.046
		P	0.036*	0.345	0.636	0.015*	0.426	0.433	0.002**	0.657
		Adjusted P	0.058	0.442	0.685	0.027*	0.503	0.503	0.005**	0.685
	Sphericity	*r*	−0.218	−0.099	−0.049	−0.249	−0.083	−0.082	0.317	0.046
		P	0.036*	0.344	0.636	0.015*	0.424	0.431	0.002**	0.661
		Adjusted P	0.058	0.442	0.685	0.027*	0.503	0.503	0.005**	0.685
	Geometric mean diameter	*r*	0.974	0.362	0.155	0.418	−0.316	−0.043	−0.270	−0.111
		P	0.000**	0.000**	0.137	0.000**	0.002**	0.685	0.010**	0.288
		Adjusted P	0.000**	0.001**	0.201	0.000**	0.005**	0.685	0.020*	0.389
	Surface area	*r*	0.974	0.363	0.156	0.416	−0.317	−0.044	−0.268	−0.112
		P	0.000**	0.000**	0.134	0.000**	0.002**	0.673	0.010**	0.286
		Adjusted P	0.000**	0.001**	0.201	0.000**	0.005**	0.685	0.020*	0.389
	Volume	*r*	0.974	0.365	0.158	0.415	−0.319	−0.046	−0.265	−0.112
		P	0.000**	0.000**	0.131	0.000**	0.002**	0.660	0.011*	0.285
		Adjusted P	0.000**	0.001**	0.201	0.000**	0.005**	0.685	0.020*	0.389
Jinding Duck	Shape index	*r*	0.071	0.038	−0.015	0.073	0.006	0.091	0.418	0.120
		P	0.588	0.768	0.911	0.581	0.966	0.495	0.001**	0.360
		Adjusted P	0.779	0.969	0.969	0.779	0.969	0.735	0.003**	0.621
	Sphericity	*r*	0.070	0.037	−0.016	0.072	0.005	0.090	0.417	0.120
		P	0.592	0.778	0.901	0.586	0.969	0.500	0.001**	0.360
		Adjusted P	0.779	0.969	0.969	0.779	0.969	0.735	0.003**	0.621
	Geometric mean diameter	*r*	0.975	0.337	−0.103	0.580	0.027	0.252	−0.006	0.138
		P	0.000**	0.008**	0.433	0.000**	0.841	0.054	0.965	0.294
		Adjusted P	0.000**	0.019*	0.698	0.000**	0.969	0.121	0.969	0.567
	Surface area	*r*	0.976	0.339	−0.101	0.578	0.024	0.250	−0.007	0.136
		P	0.000**	0.007**	0.442	0.000**	0.858	0.057	0.959	0.300
		Adjusted P	0.000**	0.019*	0.698	0.000**	0.969	0.121	0.969	0.567
	Volume	*r*	0.976	0.340	−0.100	0.577	0.022	0.248	−0.007	0.134
		P	0.000**	0.007**	0.447	0.000**	0.870	0.058	0.956	0.306
		Adjusted P	0.000**	0.019*	0.698	0.000**	0.969	0.121	0.969	0.567
Shaoxing Duck	Shape index	*r*	−0.327	−0.188	−0.031	−0.262	−0.023	−0.101	0.306	−0.050
		P	0.002**	0.076	0.771	0.013*	0.830	0.341	0.003**	0.638
		Adjusted P	0.004**	0.136	0.840	0.025*	0.840	0.482	0.007**	0.808
	Sphericity	*r*	−0.327	−0.188	−0.031	−0.261	−0.022	−0.100	0.306	−0.049
		P	0.002**	0.076	0.770	0.013*	0.840	0.347	0.003**	0.646
		Adjusted P	0.004**	0.136	0.840	0.025*	0.840	0.482	0.007**	0.808
	Geometric mean diameter	*r*	0.985	0.341	−0.143	0.429	−0.336	−0.029	−0.145	−0.026
		P	0.000**	0.001**	0.178	0.000**	0.001**	0.785	0.173	0.807
		Adjusted P	0.000**	0.003**	0.268	0.000**	0.003**	0.840	0.268	0.840
	Surface area	*r*	0.985	0.340	−0.144	0.429	−0.335	−0.027	−0.143	−0.025
		P	0.000**	0.001**	0.174	0.000**	0.001**	0.802	0.177	0.812
		Adjusted P	0.000**	0.003**	0.268	0.000**	0.003**	0.840	0.268	0.840
	Volume	*r*	0.986	0.339	−0.145	0.430	−0.333	−0.024	−0.142	−0.025
		P	0.000**	0.001**	0.173	0.000**	0.001**	0.822	0.182	0.818
		Adjusted P	0.000**	0.003**	0.268	0.000**	0.003**	0.840	0.268	0.840

Taihu Goose	Shape index	*r*	−0.195	−0.188	−0.083	−0.155	−0.067	−0.050	0.175	0.260
		P	0.120	0.133	0.513	0.220	0.598	0.694	0.163	0.036*
		Adjusted P	0.235	0.245	0.605	0.350	0.673	0.705	0.272	0.087
	Sphericity	*r*	−0.194	−0.186	−0.081	−0.154	−0.066	−0.048	0.175	0.261
		P	0.122	0.137	0.520	0.224	0.606	0.705	0.163	0.035*
		Adjusted P	0.235	0.245	0.605	0.350	0.673	0.705	0.272	0.087
	Geometric mean diameter	*r*	0.986	0.509	−0.133	0.552	−0.219	0.060	−0.120	0.145
		P	0.000**	0.000**	0.292	0.000**	0.082	0.635	0.339	0.249
		Adjusted P	0.000**	0.000**	0.384	0.000**	0.170	0.681	0.413	0.370
	Surface area	*r*	0.987	0.509	−0.133	0.552	−0.221	0.058	−0.121	0.143
		P	0.000**	0.000**	0.291	0.000**	0.079	0.645	0.337	0.254
		Adjusted P	0.000**	0.000**	0.384	0.000**	0.170	0.681	0.413	0.370
	Volume	*r*	0.987	0.509	−0.133	0.553	−0.223	0.057	−0.122	0.142
		P	0.000**	0.000**	0.292	0.000**	0.076	0.654	0.334	0.259
		Adjusted P	0.000**	0.000**	0.384	0.000**	0.170	0.681	0.413	0.370
Zhedong White Goose	Shape index	*r*	0.018	0.073	0.098	−0.070	−0.115	−0.067	0.219	0.079
		P	0.877	0.536	0.406	0.553	0.331	0.571	0.065	0.511
		Adjusted P	0.883	0.680	0.606	0.680	0.573	0.680	0.122	0.680
	Sphericity	*r*	0.017	0.072	0.097	−0.071	−0.114	−0.067	0.218	0.079
		P	0.883	0.543	0.412	0.551	0.333	0.571	0.066	0.510
		Adjusted P	0.883	0.680	0.606	0.680	0.573	0.680	0.122	0.680
	Geometric mean diameter	*r*	0.988	0.530	0.111	0.679	−0.053	0.253	0.024	0.320
		P	0.000**	0.000**	0.345	0.000**	0.656	0.030*	0.844	0.006**
		Adjusted P	0.000**	0.000**	0.573	0.000**	0.729	0.064	0.883	0.015*
	Surface area	*r*	0.988	0.528	0.109	0.677	-0.056	0.250	0.022	0.318
		P	0.000**	0.000**	0.356	0.000**	0.636	0.032*	0.856	0.006**
		Adjusted P	0.000**	0.000**	0.573	0.000**	0.723	0.066	0.883	0.015*
	Volume	*r*	0.988	0.526	0.106	0.675	-0.059	0.247	0.021	0.316
		P	0.000**	0.000**	0.367	0.000**	0.617	0.034*	0.863	0.007**
		Adjusted P	0.000**	0.000**	0.573	0.000**	0.717	0.068	0.883	0.016*

*Represents the correlations between parameters were significant ($P < 0.05$); **represents the correlations were very significant ($P < 0.01$).

Table 7. Correlations between egg geometrical parameters and shell matrix of 3 poultry species.

Breeds	Geometrical parameters	Statistics	Matrix 1 constitute	Matrix 2 constitute	Matrix 3 constitute	Matrix 1 content	Matrix 2 content	Matrix 3 content	Total matrix content	Matrix 1 amount	Matrix 2 amount	Matrix 3 amount	Total matrix amount
Hy-line Brown Chicken	Shape index	R	−0.002	−0.035	0.103	0.088	0.051	0.131	0.095	−0.040	−0.062	0.034	−0.077
		P	0.987	0.762	0.369	0.443	0.660	0.252	0.411	0.731	0.591	0.769	0.506
		Adjusted P	0.987	0.846	0.655	0.696	0.825	0.478	0.685	0.846	0.825	0.846	0.760
	Sphericity	R	−0.002	−0.035	0.103	0.089	0.052	0.132	0.096	−0.039	−0.062	0.035	−0.076
		P	0.987	0.761	0.368	0.440	0.653	0.249	0.404	0.737	0.594	0.764	0.511
		Adjusted P	0.987	0.846	0.655	0.696	0.825	0.478	0.685	0.846	0.825	0.846	0.760
	Geometric mean diameter	R	0.172	−0.178	−0.007	0.194	0.054	0.183	0.301	0.519	0.215	0.349	0.521
		P	0.133	0.119	0.954	0.089	0.639	0.109	0.008**	0.000**	0.060	0.002**	0.000**
		Adjusted P	0.279	0.277	0.987	0.272	0.825	0.277	0.036*	0.000**	0.220	0.011*	0.000**
	Surface area	R	0.171	−0.177	−0.005	0.195	0.055	0.185	0.302	0.519	0.216	0.350	0.521
		P	0.135	0.120	0.964	0.087	0.631	0.105	0.008**	0.000**	0.059	0.002**	0.000**
		Adjusted P	0.279	0.277	0.987	0.272	0.825	0.277	0.036*	0.000**	0.220	0.011*	0.000**
	Volume	R	0.170	−0.177	−0.004	0.196	0.057	0.187	0.304	0.519	0.216	0.352	0.521
		P	0.137	0.121	0.973	0.085	0.622	0.100	0.007**	0.000**	0.059	0.002**	0.000**
		Adjusted P	0.279	0.277	0.987	0.272	0.825	0.277	0.036*	0.000**	0.220	0.011*	0.000**
Shaoxing Duck	Shape index	r	0.101	−0.040	−0.178	0.136	0.094	−0.123	0.127	−0.002	−0.019	−0.162	−0.016
		P	0.374	0.729	0.113	0.232	0.408	0.278	0.263	0.987	0.867	0.151	0.887
		Adjusted P	0.628	0.872	0.628	0.628	0.646	0.628	0.628	0.991	0.950	0.628	0.950
	Sphericity	r	0.101	−0.040	−0.178	0.136	0.094	−0.122	0.127	−0.001	−0.019	−0.161	−0.016
		P	0.371	0.724	0.114	0.231	0.411	0.281	0.263	0.991	0.866	0.153	0.891
		Adjusted P	0.628	0.872	0.628	0.628	0.646	0.628	0.628	0.991	0.950	0.628	0.950
	Geometric mean diameter	r	0.040	−0.054	0.100	−0.122	−0.171	0.069	−0.157	0.112	−0.012	0.169	0.103
		P	0.727	0.636	0.377	0.283	0.132	0.543	0.168	0.327	0.915	0.133	0.366
		Adjusted P	0.872	0.855	0.628	0.628	0.628	0.786	0.628	0.628	0.950	0.628	0.628
	Surface area	r	0.040	−0.054	0.101	−0.123	−0.171	0.070	−0.158	0.111	−0.013	0.170	0.102
		P	0.725	0.635	0.374	0.278	0.131	0.540	0.165	0.331	0.912	0.131	0.371
		Adjusted P	0.872	0.855	0.628	0.628	0.628	0.786	0.628	0.628	0.950	0.628	0.628
	Volume	r	0.040	−0.054	0.101	−0.125	−0.171	0.070	−0.160	0.110	−0.013	0.170	0.101
		P	0.725	0.637	0.371	0.272	0.131	0.540	0.160	0.337	0.910	0.131	0.377
		Adjusted P	0.872	0.855	0.628	0.628	0.628	0.786	0.628	0.628	0.950	0.628	0.628
Zhedong White Goose	Shape index	r	−0.184	0.167	0.175	−0.116	0.067	0.124	−0.092	−0.095	0.004	0.110	−0.075
		P	0.117	0.155	0.135	0.325	0.570	0.298	0.433	0.423	0.972	0.352	0.527
		Adjusted P	0.322	0.322	0.322	0.483	0.668	0.468	0.554	0.554	0.974	0.499	0.644
	Sphericity	r	−0.185	0.168	0.176	−0.118	0.067	0.124	−0.094	−0.096	0.004	0.110	−0.076
		P	0.114	0.152	0.133	0.319	0.571	0.298	0.426	0.418	0.974	0.354	0.522
		Adjusted P	0.322	0.322	0.322	0.483	0.668	0.468	0.554	0.554	0.974	0.499	0.644
	Geometric mean diameter	r	−0.178	0.166	0.138	−0.016	0.219	0.160	0.028	0.356	0.560	0.467	0.416
		P	0.129	0.158	0.242	0.894	0.060	0.181	0.810	0.002**	0.000**	0.000**	0.000**
		Adjusted P	0.322	0.322	0.403	0.928	0.252	0.355	0.918	0.011*	0.000**	0.000**	0.002**
	Surface area	r	−0.181	0.169	0.140	−0.022	0.216	0.157	0.022	0.352	0.557	0.466	0.412
		P	0.123	0.151	0.234	0.854	0.064	0.187	0.851	0.002**	0.000**	0.000**	0.000**
		Adjusted P	0.322	0.322	0.402	0.921	0.252	0.355	0.921	0.011*	0.000**	0.000**	0.002**
	Volume	r	−0.184	0.171	0.142	−0.027	0.213	0.155	0.017	0.348	0.554	0.464	0.408
		P	0.118	0.145	0.228	0.818	0.069	0.194	0.889	0.003**	0.000**	0.000**	0.000**
		Adjusted P	0.322	0.322	0.402	0.918	0.252	0.356	0.928	0.012*	0.000**	0.000**	0.002**

*Represents the correlations between parameters were significant ($P < 0.05$); ** represents the correlations were very significant ($P < 0.01$).

much close to that of chicken eggs (Table 2). Moreover, based on the *SI*, our results showed that chicken eggs were comparatively round, goose eggs were much sharper, and duck eggs had an intermediate shape (Table 2). It was reported that spherical eggs might be advantageous because that spherical eggs have a minimal surface-area-to-volume ratio, and require the least amount of shell material for a given volume (Gosler et al., 2005). Hy-line Brown chicken are characterized by a high laying rate, and a laying interval between 2 consecutive eggs of about 22–26 h. Both Jinding Duck and Shaoxing Duck lay about 300 eggs in one laying year (Zhang et al., 2016), whereas Taihu Goose and Zhedong White Goose lay 4 clutches of eggs in one laying year, each clutch, respectively, contains 15 and 11 eggs, and the laying interval is about 44 h (Li et al., 2010; Yao et al., 2018). Therefore, in the case of domestication, the flight ability of poultry has been increasingly lost, and the egg shape may be mainly affected by laying rate, laying interval, or material demand of eggshell formation.

Analysis showed that egg weight, shell membrane weight, and calcified shell weight of all 5 breeds significantly correlated with 3 geometrical parameters, geometric mean diameter, surface area, and volume, among which, the egg weight can be perfectly fitted by the 3 egg geometrical parameters with very high correlation ($r > 0.97$) (Table 6). This suggests that heavier eggs had a larger contour of geometric mean diameter, surface area, and volume. In addition, the significant correlations between shell membrane weight or calcified shell weight and above 3 geometrical parameters might be indirectly affected by egg weight, because there was significant dependence of both membrane and shell weights on the egg weight (Appendix 3). Furthermore, it was assumed that egg shape (spherical, ellipticity) was fixed by the shell membranes (Stoddard et al., 2017), this assumption might based on membrane material properties because in present study, eggs of 5 breeds all showed that both egg *SI* and sphericity were independent on membrane weight (Table 6).

The calcified shell thickness seems uniform in the same egg, but the shell thickness is inhomogeneous to some extent at different points. Therefore, shell thickness uniformity was introduced (Sun et al., 2012). It has been reported that the thickness uniformity of chicken eggshells was very significantly and positively correlated with breaking strength (Sun et al., 2012). Our results revealed the correlations between shell thickness uniformity and egg geometrical parameters: in the case of Hy-line Brown Chicken and both duck breeds, eggshell thickness uniformity was very significantly and positively correlated with *SI* and sphericity (Table 6). However, in both goose breeds, shell thickness uniformity showed no significant correlation with *SI* and sphericity (Table 6). The *SI* of chicken eggs was greater than 76, eggs of both duck breeds were between 72 and 76, and eggs of both goose breeds were less than 72 (Table 2). It seemed that the significant dependence of shell thickness uniformity on the egg *SI* and/or sphericity might be applicable for eggs with a *SI* value of >72, but not applicable for eggs with a *SI* value of <72; however, it is noteworthy that we studied eggs from 180-, 500-, and 700-day old of Shaoxing Duck flocks, the *SI* values were all above 72, but in the case of 700-day-old duck, the eggshell thickness uniformity showed no significant correlation with *SI* and sphericity (Luo et al., 2020). Therefore, the significant correlations between shell thickness uniformity and *SI* or sphericity may depend on species, or ages.

Based on sampling 8,000 eggs throughout hens' entire laying cycle, it had been reported that chicken eggshell breaking strength significantly correlated with egg *SI* ($r = 0.364$, $P < 0.01$) (Sirri et al., 2018). However, the present results showed that chicken eggshell breaking strength showed no significant correlation with any of the geometrical parameters (Table 6). The difference results might be attributed to the different sample sizes or sampling methods. Furthermore, in the case of similar sample size, only goose breeds showed significant correlations between eggshell breaking strength and partial geometrical parameters, suggesting that significant correlations between poultry egg geometrical parameters and eggshell breaking strength might depend on species or breeds.

The calcified shell of avian egg, a composite bioceramic formed by $CaCO_3$ calcite crystals and a pervading organic matrix, is a predominant contributor to the mechanical properties of the eggshell. The organic matrix mainly comprises proteins and proteoglycans. In the present study, the organic matrix in calcified eggshells were dissociated into acid-insoluble, water-insoluble, and facultative-soluble (both acid and water soluble) components. We had previously reported the significant correlations between both egg weight and calcified eggshell weight and the percentage contents of all 4 groups of matrix (3 matrix components and total matrix) in per gram of shell, and the significant correlations between both calcified eggshell weight and shell thickness and the amounts of all 4 groups of matrix in an individual calcified shell (Liu et al., 2017). However, the present results showed that the constituent ratios of 3 matrix components in the whole matrix, and the percentage contents of 3 matrix components in per gram of shell showed no significant correlations with any geometrical parameters, this meant both the constituent ratios and percentage contents of 3 matrix components showed no significant effects on egg contour. The significant correlations between the amounts of 4 groups of matrix in an individual calcified shell and egg size depend on species, because in the case of duck eggs, there was no significant correlation between the amounts of 4 groups of matrix and egg size.

CONCLUSIONS

The egg geometrical parameters, adequately defined by egg length and width, would be very helpful for the evaluation of egg shape and size.

The five geometrical parameters may be grouped into 2 correlated sets, and be of high variation among 3 species of poultry.

The significant correlations between egg geometrical parameters and some eggshell or organic matrix variables depend on species or breeds.

ACKNOWLEDGMENTS

The authors thank the Zhejiang Major Scientific and Technological Project for Breeding New Agricultural Breeds of Livestock and Poultry (2016C02054-12), Qianjiang Special Expert Project of Hangzhou City of China (201929), Science and Technology Guidance Project of Hangzhou City of China (201907), Zhejiang Provincial Team Project for Animal Husbandry Technology (2021-2022), and Zhejiang Provincial Key Laboratory Project of Livestock and Poultry Ecological Health Breeding (KLGEH012) for supporting this research.

DISCLOSURES

The authors of Geometrical characteristics of eggs from 3 poultry species declared that they have no conflicts of interest to this work.

SUPPLEMENTARY DATA

Supplementary data associated with this article can be found in the online version at https://doi.org/10.1016/j.psj.2020.12.062.

REFERENCES

Barta, Z., and T. Szekely. 1997. The optimal shape of avian eggs. Funct. Ecol. 11:656–662.

Baryeh, E. A., and B. K. Mangope. 2003. Some physical properties of QP-38 variety pigeon pea. J. Food Eng. 56:59–65.

Benjamini, Y., and Y. Hochberg. 1995. Controlling the false discovery rate: a practical and powerful approach to multiple testing. J. R. Stat. Soc. B. 57:289–300.

Denys, S., J. G. Pieters, and K. Dewettinck. 2003. Combined CFD and experimental approach for determination of the surface heat transfer coefficient during thermal processing of eggs. J. Food Sci. 68:943–951.

Gosler, A. G., J. P. Higham, and S. J. Reynolds. 2005. Why are birds' eggs speckled? Ecol. Lett. 8:1105–1113.

Hutchinson, J. M. C. 2000. Three into two doesn't go: two-dimensional models of bird eggs, snail shells and plant roots. Biol. J. Linn. Soc. 70:161–187.

Kumbar, V., S. Nedomova, J. Trnka, J. Buchar, and R. Pytel. 2016. Effect of storage duration on the rheological properties of goose liquid egg products and eggshell membranes. Poult. Sci. 95:1693–1701.

Li, X., S. J. Zhang, J. Guo, Q. P. Tang, J. M. Zou, K. W. Chen, H. L. Lu, G. Y. Xu, and W. Z. Tan. 2010. Breed characteristics of Taihu goose. China Poult. 32:30–33.

Liu, Z. G., L. Z. Song, F. M. Zhang, W. Q. He, and R. J. Linhardt. 2017. Characteristics of global organic matrix in normal and pimpled chicken eggshells. Poult. Sci. 96:3775–3784.

Luo, D. K., H. L. Zhou, J. P. Dong, and Z. G. Liu. 2020. Geometrical characteristics of Shaoxing Duck eggs from 3 ages of flocks. Chin. J. Anim. Sci. 56:98–107.

Mohsenin, N. N. 1970. Page 742 in Physical Properties of Plant and Animal Material [M]. Gordon and Breach, New York, NY.

Narushin, V. G. 1997. The avian egg: geometrical description and calculation of parameters. J. Agr. Eng. Res. 68:201–205.

Perianu, C., B. De Ketelaere, B. Pluymers, W. Desmet, J. De Baerdemaeker, and E. Decuypere. 2010. Finite element approach for simulating the dynamic mechanical behavior of a chicken egg. Biosyst. Eng. 106:79–85.

Sabliov, C. M., B. E. Farkas, K. M. Keener, and P. A. Curtis. 2002. Cooling of shell eggs with cryogenic carbon dioxide: a finite element analysis of heat transfer. Lebensm. Wiss. Technol. 35:568–574.

Sarica, M., and C. Erensayin. 2004. Pages 100–160 in Poultry Products [M]. Bey-Ofset, Ankara, Turkey.

Severa, L., Š. Nedomová, J. Buchar, and J. Čupera. 2013. Novel approaches in mathematical description of hen egg geometry. Int. J. Food Prop. 16:1472–1482.

Sirri, F., M. Zampiga, A. Berardinelli, and A. Meluzzi. 2018. Variability and interaction of some egg physical and eggshell quality attributes during the entire laying hen cycle. Poult. Sci. 97:1818–1823.

Stoddard, M. C., E. H. Yong, D. Akkaynak, C. Sheard, J. A. Tobias, and L. Mahadevan. 2017. Avian egg shape: Form, function, and evolution. Science 356:1249–1254.

Sun, C. J., S. R. Chen, G. Y. Xu, X. M. Liu, and N. Yang. 2012. Global variation and uniformity of eggshell thickness for chicken eggs. Poult. Sci. 91:2718–2721.

Yao, Y., Z. F. Cao, Y. Z. Yang, T. T. Gu, Q. Xu, Y. Q. Bian, G. H. Chen, and W. M. Zhao. 2018. Laying and nesting behavior of Zhedong white goose. Chin. J. Anim. Sci. 54:113–116.

Zhang, J. Q., H. B. Zhang, and M. C. Diao. 2016. Laying curve of cage-reared Shaoxing duck. Hubei J. Anim. Vet. Sci. 37:8–9.