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‘Eggology’ and mathematics of a quail egg: An innovative non-destructive technology for evaluating egg parameters in Japanese quail

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A R T I C L E I N F O

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A B S T R A C T

Quail eggs, the smallest ones among poultry species, require special methodological aspects for their non-destructive examination and quality analysis. Using eggs from a cross between the Japanese and Texas breeds, we devised a methodology for defining the main geometric parameters of quail eggs. Calculation formulae were proposed to estimate indirectly egg volume and surface area. Our findings on the weights of structural egg components enabled to obtain mathematical equations for computing the weights of shell, yolk and albumen, depending on the complex of measured parameters including the egg weight, its volume and surface area. When taken as a whole, the results of our study can be regarded as the most thorough methodological approach to date for the execution of comprehensive investigations of quail egg quality. They will be applicable and instrumental in areas of food research and emerging technologies, including the aspects of storage, packing, and processing of quail eggs.

1. Introduction

Rearing of the Japanese quail (*Coturnix japonica* Temminck and Schlegel, 1848) currently acquire more and more attraction (Volkovoy and Bondarenko, 1989; Lukanov and Pavlova, 2020; Lan et al., 2021). Quail eggs are in a growing consumption demand in the world (Fig. 1) in view of their nutritional qualities, as well as dietary, functional and possible therapeutic value (Tunsaringkarn et al., 2013; Bayomy et al., 2017; Ali and El-Aziz, 2019). According to Allarakha and Uttekar (2022), there are many benefits of quail eggs for human health, such as a protein source containing essential amino acids in appropriate proportions; immunity boosting because of the presence of vitamin A as well as antioxidants; an aid to weight loss because of low calorific content; a promoter of brain, bone, muscle and heart health because of the presence of choline, folate, lipids antioxidants (brain) vitamin D calcium, protein, calcium, phosphorus, magnesium (musculoskeletal)

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Fig. 1. A sample of wholesale commercial quail egg tray (authors' own photo).

polyunsaturated lipids, antioxidants, iron and vitamin B_{12} (cardiovascular). Their beneficial role in alleviating eosinophilic esophagitis gastritis and peptic ulcers has been demonstrated as well as a role in boosting liver health and helping to eliminate bodily wastes. The presence of lutein, zeaxanthin, and selenium is thought to be good for eye health, protecting against the damaging effect of free radicals and thereby protecting against cataracts and macular degeneration. Skin and hair benefits are noted because of the presence of various lipids vitamins, minerals, and protein and proteins; and, finally, the presence of vitamins and ovomucoid protein may help combat allergies such as allergic rhinitis and asthma (Tessari, 2019; Mnisi et al., 2021; Allarakha and Uttekar, 2022).

To facilitate this increase in demand and consumption, the transition of quail farming from an amateur pursuit to a commercial basis has been accompanied by changes in technological approaches to the management of quails and processing of their products (Ryabokon et al., 2005; Podstreshnyi et al., 2010; Podstreshnyi and Tereshchenko 2012a, b; Batool et al., 2023; Sunkara et al., 2023). Such measures include a more active use of innovative scientific and experimental solutions related to the fundamental issues of obtaining high-quality produce at all stages of commercial quail raising (e.g., Baumgartner and Bondarenko, 1989; Mehaisen et al., 2019; El-Attrouny and Iraqi, 2021; German et al., 2022).

Despite the huge amount of research already carried out (and ongoing) on chicken eggs, their quail 'co-brethren' possess some characteristic nuances that limit the direct transfer of findings from one species to another there is the issue of the difference in egg weight (W) that is 4–7 times greater in most commercial chickens compared to Japanese quail. Secondly, the colored shell of quail eggs makes it difficult, and sometimes impossible, to apply such classical methods of egg quality assessment as transillumination (candling) (Tagirov et al., 2009). Thirdly, their small size and relatively thin shell require a more thorough and extremely cautious approach to the process of measuring an experimental sample. As a consequence, the analytical toolbox used in studies of quail eggs is most often limited to only a few parameters that are most accessible for measurements. These can be roughly divided into the following three subgroups: (i) egg weight, W (Insko et al., 1971; Woodward et al., 1987; Sarica and Soley, 1995; Alkan et al., 2008; Hegab and Hanafy, 2019; Aryee et al., 2020; Al-Tikriti and Al-Nassery, 2023); (ii) shell pigmentation (Soliman et al., 2000; Galíndez et al., 2010; Idahor et al., 2014; Gutiérrez et al., 2021); and (iii) the egg's geometric features expressed by its shape index (B/L), i.e., the ratio of maximum breadth (B) to length (L) (Sarı et al., 2010; Taskin et al., 2015; Kostaman and Sopiyana, 2021; Çal and Aktan, 2021; Gutiérrez et al., 2021).

The classic Latin expression *ab ovo* refers to the study of eggs and is one of the original, and perhaps most complex avenues of scientific research. While there is a term 'oology' for an ornithology subdiscipline studying wild bird eggs, nests and breeding behavior (e.g., Romanov et al., 1994, 1999; Chernikov et al., 1994; White, 2020), a colloquial term 'eggology' (e.g., Richmond, 2020) may be more appropriate to embrace all (including mathematical) aspects of research on domestic and wild bird eggs. Avian eggs are the basis for reproduction, a keen interest of ecology and one of the most valuable and widespread food products. To conduct comprehensive 'eggology' research on quail eggs therefore, it is advisable to employ a wider range of indicators that include both external characteristics and content parameters than has previously been used. Indeed, a small number of studies beyond the aforementioned three typical directions have involved more in-depth parameters. For instance, Kostaman and Sopiyana (2021) and Çal and Aktan (2021) suggested taking into account the influence of not only W, but also the volume (V) of quail eggs, as well as their surface area (S). Recently, we reported a pilot study that included examination of various morphometric parameters, both external and internal, and quality indicators of quail eggs using non-destructive and invasive methods (German et al., 2022, 2023; Prituzhalova et al., 2023). Other researchers determined that a number of economically important traits, e.g., the sex ratio of embryos in quail eggs, may be influenced not by the simplest index characterizing the egg shape, but by more complex geometric measurements (Idahor et al., 2014; Sati et al., 2019). Considerable prospects open up before 'eggologists' if non-destructive exploration of the quail egg content's parameters is possible. Attempts to develop this research avenue were made, for example, by Narushin et al. (2001) and Seker (2004). However, only one parameter, i.e., W, was used by those authors as an influencing variable, which was clearly insufficient for the required calculation accuracy.

Thus, science-based quail production is in need of developing a more accurate methodological guidelines for assessing the external and internal parameters of eggs. The objective of this research was to thus formulate in detail a mathematical and methodological apparatus for measuring and calculating adequate indicators of the geometry of quail eggs, their V and S, as well as weight components of shell, yolk and albumen.

2. Material and methods

To accomplish the stated research objective, 54 quail eggs were collected from F_2 progenies of a cross between the Japanese and Texas breeds that were aged 2–3 months. Each egg was weighed (W) with an accuracy of 0.01 g on an electronic balance using a measuring complex of the Egg Quality Testing System (Stable Micro Systems, Godalming, UK). Using a caliper, L and B of the eggs were determined with an accuracy of 0.1 mm. In view of the small size of quail eggs, quite high error rates are expected when measuring the value of B. Even a slight distortion of the measuring device leads to inaccurate reproduction of the result. In this regard, all eggs were photographed following the respective procedure described in Narushin et al. (2020a). Afterwards, using these images and the Microsoft Picture Manager software, the L and B values were measured with an accuracy of 1 pixel, as well as the distance (w) of the shift of the B axis from the egg center (Narushin et al., 2020b) and the egg diameter ($D_{L/4}$) at a point separated from the pointy end by $L/4$ (Narushin et al., 2021a). Knowing the size of L, respectively in mm and pixels, we converted the measurements and other geometric parameters, i.e., B, w and $D_{L/4}$, into the metric system. The V values of eggs were measured using the Archimedes' principle, i.e., by weighing them in water. The calculation of egg density (D) was performed as the ratio of W to V.

Since it is impossible to measure S accurately and adequately using the measuring equipment, we employed a technique based on the principles of topology (e.g., Gamelin and Greene, 1999) that we successfully used in our previous studies in relation to the calculation of similar egg parameters in other bird species (Narushin, 1993, 1997, 2001; Narushin et al., 2020a). In accordance with this method, the egg is conditionally transformed into a certain standard geometric figure of the same volume, for which the standard formulae for calculating S are established. As such figures applied to chicken eggs, Narushin et al. (2020a) examined several models, and the most accurate of them turned out to be an ellipsoid. In this case, the S value was computed based on the formula for ellipsoids (Narushin et al., 2020a):

$$S = 2.418\left(\frac{B}{L}\right)^{\frac{2}{3}} \cdot \left(\frac{L}{B} \cdot \frac{\arcsin\sqrt{1-\frac{B^2}{L^2}}}{\sqrt{1-\frac{B^2}{L^2}}} + 1\right) \cdot V^{\frac{2}{3}} \tag{1}$$

where S is egg surface area (in cm^2), V is egg volume (in cm^3), L is egg length (in cm), B is egg maximum breadth (in cm).

We assumed that the geometric contour of a quail egg is somewhat different from that of a chicken egg and, therefore, comparative studies of possible variants of profiles were first planned. Narushin et al. (2020b, 2021a) demonstrated earlier that the $D_{L/4}$ value can be used as the most informative indicator for such comparisons, and advised to use it as a dimensionless index $D_{L/4}/B$. Then, its value measured for a particular quail egg can be compared with two boundary variants spaced on the conditional scale of egg profiles, i.e., between the pyriform egg, whose shape conforms to a parabola, and the classic ovoid that corresponds to the Hügelschäffer's model (Narushin et al., 2020b, 2021a). Based on the previously derived formulae for each of the two models (Narushin et al., 2022a), we slightly transformed them for our case and determined the corresponding indices according to the following expressions:

for the pyriform shape:

$$\frac{D_{L/4(\mathrm{pyr})}}{B} = \frac{0.707}{\sqrt{1+2\frac{w}{L}}} \tag{2}$$

for the classic ovoid shape:

$$\frac{D_{L/4(ov)}}{B} = \frac{0.866}{\sqrt{1+2\frac{w}{L}+4\left(\frac{w}{L}\right)^2}} \tag{3}$$

If we take the values of the indices calculated by formulae (2) and (3) that we called "conicity indices" as the limits of the scale from 0 % to 100 %, then the conditional percentage of quail egg conicity (CI) can be calculated by the following equation:

$$CI = \frac{D_{L/4} - D_{L/4(\mathrm{pyr})}}{D_{L/4(ov)} - D_{L/4(\mathrm{pyr})}} \cdot 100 \tag{4}$$

Thus, if the result of the comparative analysis would demonstrate a greater adherence of the profile of quail eggs to the classic ovoid (similar to chicken eggs), Eq. (1) was applied to calculate their S value. If the profile of a quail egg tended to be more pyriform, the respective calculation formulae presented in Narushin et al. (2022a) were used.

After external measurements, all eggs were broken, separating the shell, yolk and albumen from each other following the standard procedure (e.g., Moiseeva and Tolokonnikova, 1966, 1973; Moiseeva, 1970). The shell was thoroughly washed from the remnants of the contents without separating the shell membrane, dried in air for a day, and weighed (W_s) with an accuracy of 0.01 g. The yolk was weighed (W_y), and albumen weight (W_a) was calculated as the difference: $W_a = W - W_s - W_y$.

The degree of correspondence between the calculated and true parameter values was assessed with a mean percentage error, ε (e.g., Makridakis et al., 1982):

$$\varepsilon = \frac{1}{n} \cdot \sum_{1}^{n} \left|\frac{v_1 - v_2}{v_1}\right| \cdot 100\% \tag{5}$$

where n is number of measurements (according to the number of eggs studied, i.e., 54), and v_1 and v_2 are values of a corresponding parameter defined as a direct measurement (v_1) and the calculated one (v_2).

The STATISTICA 5.5 software (StatSoft, Inc./TIBCO, Palo Alto, CA, USA) and computational Excel applications were used to process and analyze the results.

3. Results and discussion

The results of measurements and/or corresponding calculations of the quail egg parameters are presented in Table 1.

To confirm our assumption about a possible error in measuring B with a caliper, we compared these values with those resulted from measurements taken on images of eggs. The respective error averaged 0.5 % with a range variation from zero to 1.7 %, which, in principle, can be considered acceptable. However, we would recommend using a computer measurement of the B value, as well as other geometric parameters. It is then advised to recalculate the pixel measurement system into the metric one according to the L value of the egg initially measured using a caliper.

Having the necessary set of experimental data, we carried out their subsequent detailed analysis towards the successful implementation of the main study objective.

3.1. Geometric features of quail eggs

In our previous studies (Narushin, 2001; Narushin et al., 2021a, 2022a, 2023b), we demonstrated a successful analysis of the avian egg contours using both geometric indices and mathematical models that allow us to reproduce functionally the egg profile in its digital image. As possible indices, the following set of measured parameter ratios was proposed: B/L, w/L, and $D_{L/4}/B$. The latter can be especially informative, as it indicates type of eggs (pyriform or ovoid) to which one can attribute a particular egg. In this respect, we paid a close attention to the estimated characteristic for this indicator $D_{L/4}$ as expressed in another proposed conicity coefficient, CI (Eqn4). Since we needed to determine the respective ratios for ovoid and pyriform egg profiles in order to estimate CI, the values of $D_{L/4}/B$ were calculated according to the above Eqs. (2) and (3). The results of calculations of these geometric indices are presented in Table 2.

Analyzing the data in Table 2, it can be stated that, judging by B/L and the vertical axis shift index (w/L), quail eggs are extremely similar in shape to chicken eggs (e.g., Narushin et al., 2020b). However, their CI value was lower (on average, by 27 %) than the classical ovoid that

Table 1
Data of measured and calculated quail egg variables.

Parameters	Mean	Standard deviation
Egg weights, W (g)	11.78	0.931
Length, L (cm)	3.31	0.105
Max breadth, B (cm)	2.56	0.075
Shift of the B axis from the egg center, w (cm)	0.19	0.045
Egg diameter at a distance of 1/4 of its length from the pointy end, $D_{L/4}$ (cm)	1.99	0.075
Egg volume, V (cm^3)	11.04	0.877
Egg density, D (g/cm^3)	1.067	0.009
Shell weight, W_s (g)	1.52	0.146
Yolk weight, W_y (g)	3.84	0.561
Albumen weight, W_a (g)	6.42	0.714

Table 2
Data of calculated geometrical indices for quail eggs.

Parameters	Mean	Standard deviation
B/L	0.775	0.019
w/L	0.059	0.013
$D_{L/4}/B$	0.775	0.018
$D_{L/4(\mathrm{pyr})}/B$	0.669	0.008
$D_{L/4(\mathrm{ov})}/B$	0.814	0.011
CI, %	72.8	8.03

conforms to the chicken egg profiles mathematically corresponding to the Hügelschäffer's model. On the other hand, conicity of quail eggs was not as pronounced as in pyriform egg profiles mathematically conforming to the parabolic function. Visualization of the conicity degree of quail eggs in comparison with the boundary data of pyriform and ovoid models is shown in Fig. 2.

In addition to using our proposed indices, i.e., B/L, w/L and $D_{L/4}/B$, for estimation of geometric parameters, considerable promising prospects for the study of quail eggs can also be resulted from a mathematical description of their contours. To create such a model, we derived a certain standard geometric figure, with its parameters suitable for defining the presence or absence of deviations in the shape of a particular egg (Narushin et al., 2023b). Hereby, integral geometry formulae can be applied to calculate such parameters as V, S, circumference, normal projection area, and curvature at any point on the egg surface (Narushin et al., 2021b, 2022a). Moreover, this approach allows for obtaining some other, possibly unique, indices directly related to quail breeding or other useful criteria when conducting a large range of investigations.

Based on the preliminary index estimation, the contours of quail eggs do not clearly conform to either pyriform or Hügelschäffer's models (e.g., Petrović and Malešević, 2022, 2023; Petrović et al., 2023), but rather lie between them. Hence, the most suitable for application will be the improved universal model for any avian egg profile that we recently derived (Narushin et al., 2023b) as follows:

$$Y = \pm\frac{B}{2}\left[\frac{1}{\sqrt{1+4\frac{(x+w)^2}{L^2-4x^2}}} + \left(\sqrt{\frac{1+4\frac{(w-w_p)^2}{L^2-4w^2}}{1+4\frac{(x+w_p)^2}{L^2-4x^2}}} - \frac{1}{\sqrt{1+4\frac{(x+w)^2}{L^2-4x^2}}}\right)\left(1+\frac{x+w}{\sqrt{(x+w)^2}}\right)\left(\frac{x}{L}+\frac{1}{4}\right)\right] \tag{6}$$

In addition to the parameters already mentioned earlier in this article, Eqn6 includes the w_p indicator that can be calculated by the following formula:

$$w_p = L\left(\frac{\left(\frac{D_{L/4}}{B}\right)^2\left(1-4\left(\frac{w}{L}\right)^2\right)+3\frac{w}{L}}{3-4\left(\frac{D_{L/4}}{B}\right)^2\left(1-4\left(\frac{w}{L}\right)^2\right)} - \sqrt{\left(\frac{\left(\frac{D_{L/4}}{B}\right)^2\left(1-4\left(\frac{w}{L}\right)^2\right)+3\frac{w}{L}}{3-4\left(\frac{D_{L/4}}{B}\right)^2\left(1-4\left(\frac{w}{L}\right)^2\right)}\right)^2-\frac{1}{4}}\right) \tag{7}$$

As a specific example of the applicability of the improved universal model (Narushin et al., 2023b) to describe the contours of quail eggs, we picked three egg profiles: (1) typical, of an average shape ($D_{L/4}/B = 0.775$; Fig. 3A); (2) the most conical ($D_{L/4}/B = 0.725$; Fig. 3B); and (3) rounded ($D_{L/4}/B = 0.826$; Fig. 3C).

An analysis of the obtained images (Fig. 3A–C) confirmed the correctness of the mathematical description of all the characteristic features inherent in quail eggs using the improved universal bird egg model (Eqn6).

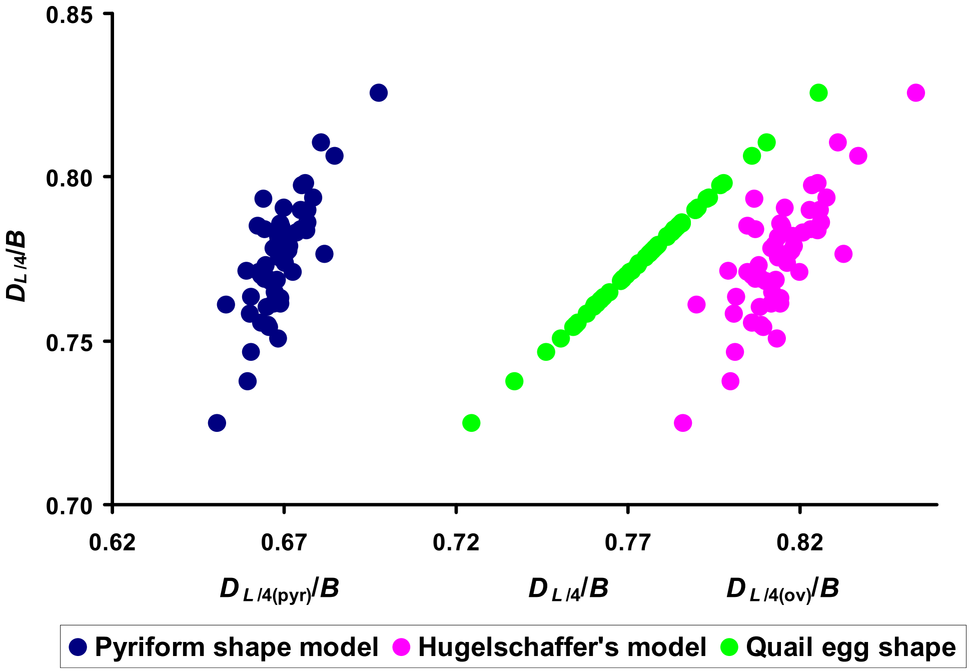

Fig. 2. Visualization of the $D_{L/4}/B$ index of quail eggs in comparison with similar ones for pear-shaped eggs, mathematically determined by the parabolic function, $D_{L/4(\mathrm{pyr})}/B$ (Eqn2) and for chicken, that is, the classic ovoid, mathematically expressed by Hügelschäffer's model, $D_{L/4(\mathrm{ov})}/B$ (Eqn3).

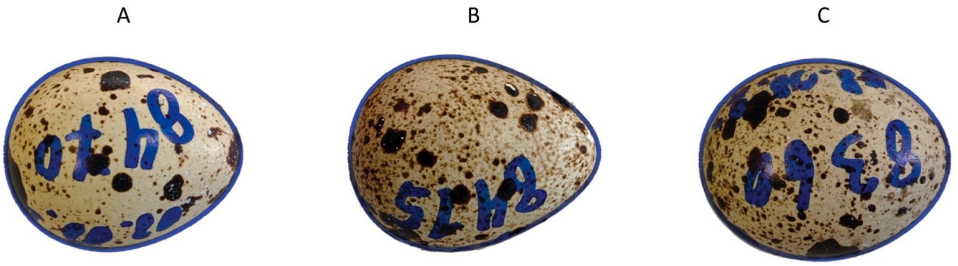

Fig. 3. Japanese quail (*Coturnix japonica*) eggs that have the contours mathematically described by the improved universal model (Narushin et al., 2023b) according to Eqn6 (blue line). (A) Egg 1 ($D_{L/4}/B = 0.775$); (B) egg 2 ($D_{L/4}/B = 0.725$); (C) egg 3 ($D_{L/4}/B = 0.826$).

3.2. *Mathematical formulae for calculating V and S of quail eggs*

Based on the analysis in the previous Section (3.1) that suggested a closer relationship between the contours of quail eggs and the classic ovoid (Fig. 2), we can confidently assert the adequacy of using Eq. 1 to calculate the initial values of S. The obtained S values in the framework of the measured values of quail eggs were within 24.3 ± 1.34 cm^2.

We assert therefore that the most accurate method for determining V and S is the one described in Section 2, i.e., using the Archimedes' principle for V and formula (1) for S that includes V as one of its variables. However, often, when conducting experiments, it is undesirable to dip the egg into water so as not to wash off the cuticle, the protective layer covering the surface of the egg. As for commercial use, this method is completely inapplicable, due to the complexity and impossibility of automating the measurement process. In this regard, many developments are aimed at creating more convenient and simple calculation methods based on geometric measurements of eggs. In connection with this need, we developed and tested a number of approaches for calculating V and S, based on measurements of two (Narushin, 2005; Narushin et al., 2021c, 2022b), three (Narushin, 1993, 1997, 2001; Narushin et al., 2020a, b, 2021b, c) and four (Narushin et al., 2022a) parameters. Since most of the equations were obtained on the example of chicken eggs, their analysis in relation to quail eggs, as well as the choice of the most adequate one, was the aim of this stage of our research.

Table 3 shows the formulae used by us for the possible computation of V and S of quail eggs involved in the experiment, as well as the error ($\mathcal{E}$) values (in %) calculated according to Eq. 5 and obtained as a result of their application.

Table 3
Calculation formulae for defining V and S of quail eggs.

Equation	Reference	$\mathcal{E}$, % (Eq.5)
$V = 0.5202LB^2 - 0.4065$(8)	Narushin et al. (2021c)	1.60
$S = 0.933B(B + 2.343L)$(9)	Narushin et al. (2021c)	1.47
$V = \frac{0.5233B^2(L^2 + 0.0071Lw - 0.8565w^2)}{L}$(10)	Narushin et al. (2021b)	2.89
$S = \pi LB\left(\left(0.043\frac{w}{L} + 0.292\right)\frac{B}{L} - 0.061\frac{w}{L} + 0.704\right)$(11)	Narushin et al. (2021b)	2.13
$V = 0.992LB^2\left[\left(\frac{D_{L/4}}{B} - 0.426\right)\frac{w}{L} + 0.396\frac{D_{L/4}}{B} + 0.182\right]$(12)	Narushin et al. (2022a)	1.10
$S = 0.2447LB\left\{\left(\frac{B}{L} - 0.0838\right)\frac{w}{L} + 3.5039\frac{B}{L} + 8.3032 - 39.2419\left(\frac{D_{L/4}}{B} + 0.5165\frac{w}{L} - 0.7016\right) \cdot \left[\left(\frac{B^2}{L^2} - 1.546\frac{B}{L} - 0.1836\right)\left(\frac{w}{L} + 0.1016\right)\frac{w}{L} + 0.1153\left(\frac{B}{L}\right)^2 - 0.2112\frac{B}{L} - 0.0545\right]\right\}$(13)	Narushin et al. (2022a)	0.67

The results of Table 3 suggest a sufficient degree of practical suitability of all previously derived formulae for calculating V and S, with some increase in accuracy with an increase in the number of measured parameters involved in the calculation. Taking into account the fact that even the current standard software makes it easy to carry out the most complex calculations, Eq. 13, despite its cumbersomeness, can be recommended as a base for calculating S.

Sometimes, researchers go back and revisit the results of their previous experiments, in which the required measurements of all parameters were not always carried out. That is, it is possible that many of the data obtained earlier in the study of quail eggs could be interpreted taking into account the emerged possibility of calculating V and S. However, if it is possible to operate with only a limited set of measurements, say, the values of L and B, we then suggest with confidence to use Equations (8) and (9) for these purposes.

Nevertheless, in terms of the calculation accuracy, we also decided to examine the factor of the maximum (and not just the average) error. There were no causes for concern about the computation of S value, since the maximum value of $\mathcal{E}$ for Eq. 13 was 2 %, and for Eq. 9 it did not exceed 4 %. On the other hand, the calculation of V following Eq 8 could lead to a maximum error of 7 %. While the run-out data was not so obvious when comparing the calculated V with its true value (Fig. 4A), this was quite noticeable when the calculated V value (Eq. 8) was used to determine D (Fig. 4B).

A very wide range of D values (Fig. 4B) evidenced in favor of an increased accuracy of the results of calculating V. At the same time, this was the case for both Eq. 8 and more accurate, four-parameter Eq. 12. If we take, as a comparison criterion, the correlation coefficient (R) between the true and calculated D values, then, $R = 0.447$ ($p < 0.05$) when using the calculation formula (8) in determining D. When the D value was determined using Eq. 12, the correlation grew to $R = 0.515$ ($p < 0.05$). However, we tried to improve this indicator using the outcome of parameter measurements from our experiment. As a result, based on Eq. 12, it was converted to the following:

$$V = LB^2\left(0.199 + 1.025\frac{w}{L} + 0.388\frac{D_{L/4}}{B} - 1.157\frac{w}{L}\cdot\frac{D_{L/4}}{B}\right) \tag{13}$$

The computation of the V value using Eq. 13 provided an average error of 0.95 % with a maximum of 2.9 %, which was somewhat higher than the result of calculation using Eq. 12. When recalculating the D value using Eq. 13, the new data correlated with true D values at 0.544 ($p < 0.01$). We managed to increase slightly the accuracy of both the result itself and the significance of the correlation coefficient. However, the obtained values were still far from the true values (Fig. 5), obviously due to the lower values of W and V in quail eggs. In this respect, when conducting experiments, we would recommend identifying the V value by the Archimedes' method, i.e., by dipping an egg into water.

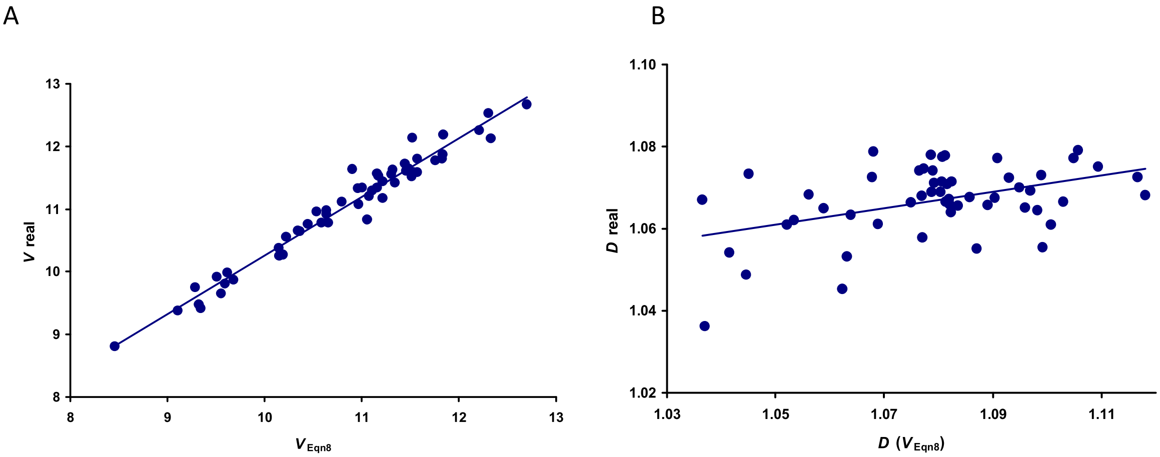

Fig. 4. Visualization of the results when comparing the true and calculated values of (A) V (Eq. 8) and (B) D that was determined using the calculated V value according to Eq. 8.

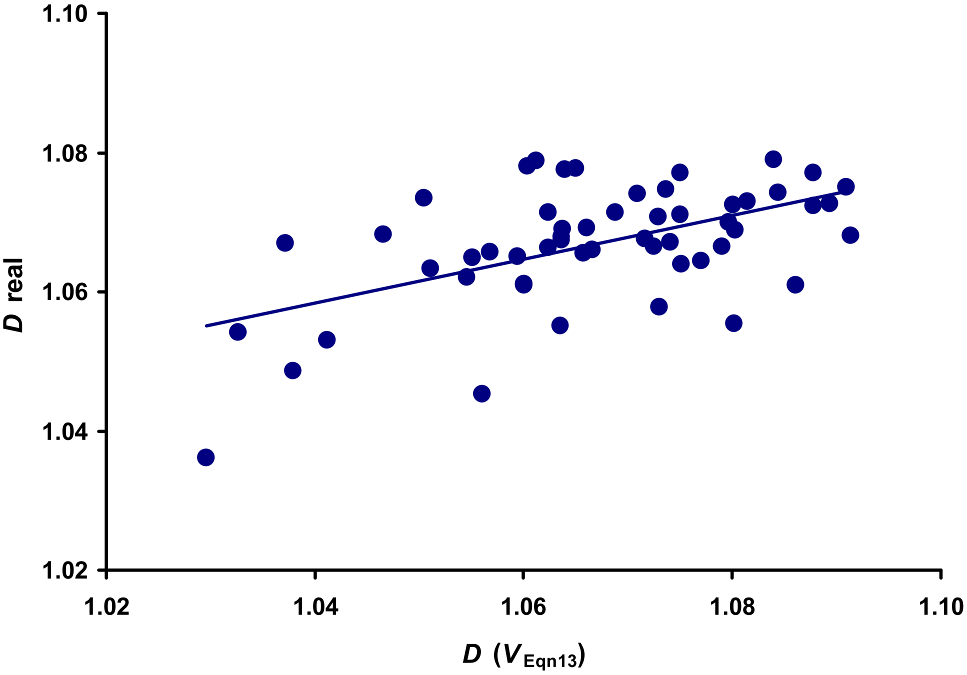

Fig. 5. Visualization of the results of comparing the true and computed values of D that was determined using the V value obtained by calculation according to Eq. 13.

3.3. *Mathematical dependencies for calculating the weight fractions of quail eggs' structural components*

One of the key aims of researchers working with oological ('eggological') material is to look inside the egg but keep it intact. This opens up many opportunities for working out the innovative incubation technology, in particular, non-invasive pre-hatching sorting of eggs. In this regard, we made an attempt to analyze which of the measured parameters were most closely related to the weight of the egg's structural components, i.e., its shell, yolk, and albumen. The results of the respective correlation analysis are presented in Table 4.

The maximum correlation coefficients were observed between the weight structural components (W_s, W_y and W_a) and W (Table 4). Visualization of these relationships is shown in Fig. 6.

The obtained graphic dependences were approximated by the following equations:

Table 4
Correlation of measured egg variables with shell (W_s), yolk (W_y) and albumen (W_a) weights.

Parameters	Correlation with		
	W_s	W_y	W_a
Egg weight, W (g)	0.601^a	0.564^a	0.737^a
Length, L (cm)	0.385^a	0.491^a	0.616^a
Max breadth, B (cm)	0.580^a	0.577^a	0.662^a
Egg density, D (g/cm^3)	0.384^a	-0.241	0.128
Egg volume, V (cm^3)	0.559^a	0.588^a	0.720^a
Surface area, S (cm^2)	0.553^a	0.586^a	0.721^a
Shift of the B axis from the egg center, w (cm)	0.078	0.151	0.089
Egg diameter at a distance of 1/4 of its length from the pointy end, $D_{L/4}$ (cm)	0.489^a	0.389^a	0.584^a

^{a} $p < 0.05$; the values without any index are insignificant.

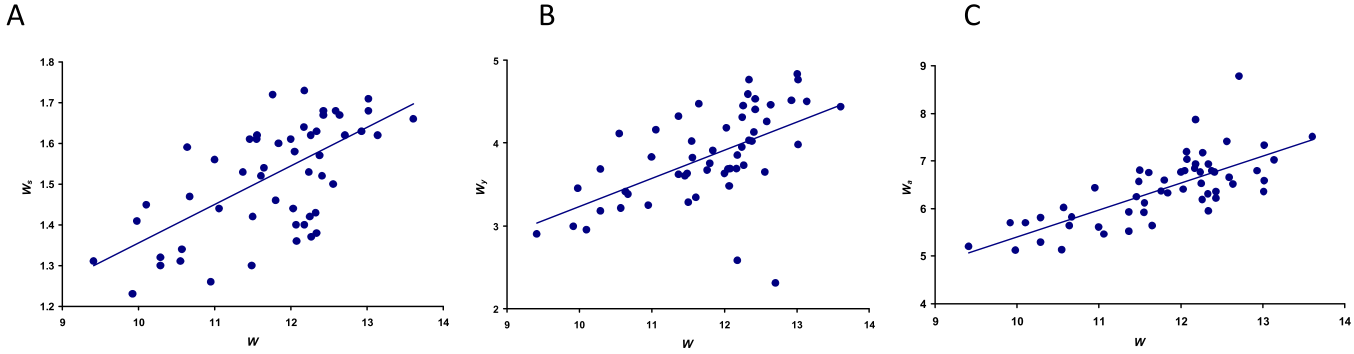

Fig. 6. Visualization of correlation analysis results between egg weight, W, and weights of shell, W_s (A); yolk, W_y (B); and albumen, W_a (C).

$$W_s = 0.094W + 0.412 \tag{14}$$

$$R^2 = 0.361\ (p < 0.01)$$

$$W_y = 0.34W - 0.17 \tag{15}$$

$$R^2 = 0.319\ (p < 0.01)$$

$$W_a = 0.565W - 0.242 \tag{16}$$

$$R^2 = 0.543\ (p < 0.01),$$

where W, W_s, W_y and W_a were measured in g.

In our previous studies (Narushin, 1998a, b; Narushin et al., 2004, 2023a), we demonstrated that the approximation result can be improved if several key egg parameters are taken into account as influencing variables. The most effective for such prediction is a set of parameters W, V and S. In this regard, we performed the appropriate calculations that enabled to obtain the following dependencies:

$$W_s = 433.204W^{4.967}V^{-1.038}S^{-4.833} \tag{17}$$

$$R^2 = 0.510\ (p < 0.01)$$

$$W_y = 594.675W^{-3.325}V^{7.452}S^{-4.623} \tag{18}$$

$$R^2 = 0.385\ (p < 0.01)$$

$$W_a = 0.00076W^{2.957}V^{-4.572}S^{3.994} \tag{19}$$

$$R^2 = 0.564\ (p < 0.01),$$

where W, W_s, W_y and W_a were measured in g, V in cm^3, and S in cm^2.

Comparison of the obtained formulae (17) to (19) with one-parameter Eqs. 14 to 16 suggested an increased prediction accuracy (Fig. 7), which supported the validity and effectiveness of the synergy principle applied.

However, the issue of increasing the accuracy of calculations of internal morphological parameters of quail eggs remains open. In order to improve the prediction power, we can recommend expanding the set of initial non-destructive measurements. One of these can be the method of non-destructive shell deformation (e.g., Narushin et al., 2021d) that, in addition to increasing the prediction accuracy of shell parameters, can also be successfully used to calculate egg content's indicators (Narushin et al., 2023a).

4. Conclusions

The results of this study using innovative non-destructive technology can be characterized as the description of the mathematical harmony of a quail's egg, demonstrating interconnectedness and interdependence of its key parameters. We established that four dimensions of geometric egg characteristics, namely, L, B, w and $D_{L/4}$, can be sufficient to (i) describe mathematically the geometry of the egg contours, both with the help of key indices and by mathematical modeling of the egg profile; (ii) calculate accurately V and S of the egg; and (iii) while leaving the egg intact, look under the shell by calculating the weights of structural components, i.e., shell, yolk, and albumen.

Collectively, our findings can be considered the most complete methodological approach to date for the implementation of fully-fledged 'eggology' research in Japanese quail. They will be critical in further investigation aimed at unraveling the issues of storage, packaging and processing of quail eggs.

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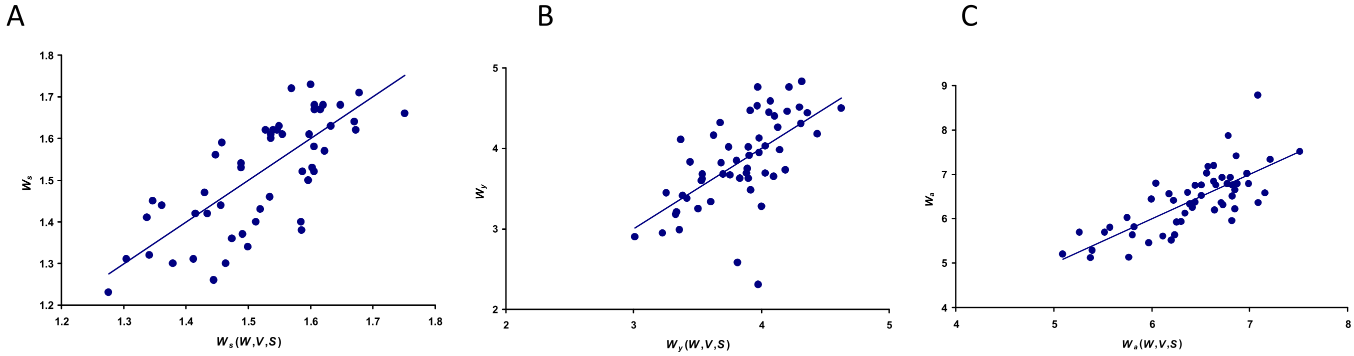

Fig. 7. Visualization of the correlation analysis results of between a set of parameters, including egg weight, W, its volume, V, and surface area, S, relative to weights of shell, W_s (A); yolk, W_y (B); and albumen, W_a (C).

Human and animal rights

These experiments comply with the ARRIVE guidelines and were carried out in accordance with the U.K. Animals (Scientific Procedures) Act, 1986 and associated guidelines, EU Directive 2010/63/EU for animal experiments, and the authors verify that such guidelines have been followed.

CRediT authorship contribution statement

Danila A. Sotnikov: Investigation. **Natalia A. Volkova:** Data curation, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Anastasia N. Vetokh:** Investigation, Validation. **Michael N. Romanov:** Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Natalia A. Zinovieva:** Funding acquisition, Project administration, Supervision, Writing – review & editing. **Ludmila A. Volkova:** Investigation, Validation. **Darren K. Griffin:** Supervision, Writing – review & editing. **Valeriy G. Narushin:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no conflicts of interest.

Data availability

Data will be made available upon request.

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