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ORIGINAL ARTICLE

Shell quality parameters of Japanese quail (*Coturnix japonica*) eggs as estimated by non-destructive testing technology

Short running title: **Quail shell parameters non-invasively tested**

Valeriy G. Narushin,¹ Natalia A. Volkova,^{2,*} Alan Yu. Dzhagaev,² Zarina V. Gagieva,² Ludmila A. Volkova,² Darren K. Griffin,^{3,4,5} Michael N. Romanov,^{2,3,5,*} Natalia A. Zinovieva²

¹ Vita-Market Lab, Zaporizhya, Ukraine.

² L. K. Ernst Federal Research Centre for Animal Husbandry, Dubrovitsy, Podolsk, Moscow Oblast, Russia.

³ School of Natural Sciences, University of Kent, Canterbury, Kent, UK.

⁴ Royal Veterinary College, University of London, London, UK.

⁵ Animal Genomics and Bioresource Research Unit (AGB Research Unit), Faculty of Science, Kasetsart University, Chatuchak, Bangkok, Thailand.

* Corresponding authors.

E-mail addresses: natavolkova@inbox.ru (N. A. Volkova); m.romanov@kent.ac.uk (M. N. Romanov)

Valeriy G. Narushin: <https://orcid.org/0000-0001-6799-6605>, e-mail: val@vitamarket.com.ua

Natalia A. Volkova: <https://orcid.org/0000-0001-7191-3550>, e-mail: natavolkova@inbox.ru

Alan Yu. Dzhagaev: <https://orcid.org/0000-0001-7818-0142>, e-mail: alan_dz@inbox.ru

Zarina V. Gagieva: <https://orcid.org/0009-0002-1473-629X>, e-mail: gagievazarina13@mail.ru

Ludmila A. Volkova: <https://orcid.org/0000-0002-9407-3686>, e-mail: ludavolkova@inbox.ru

Darren K. Griffin: <https://orcid.org/0000-0001-7595-3226>, e-mail: D.K.Griffin@kent.ac.uk

Michael N. Romanov: <https://orcid.org/0000-0003-3584-4644>, e-mail: m.romanov@kent.ac.uk

Natalia A. Zinovieva: <https://orcid.org/0000-0003-4017-6863>, e-mail: n_zinovieva@mail.ru

Abstract: The quality parameters of quail eggshells find extensive utility in studies of production efficiency and basic biology. Non-destructive evaluation methods are of particular relevance. Herein, we developed a non-destructive technology for assaying such shell characteristics as shell strength (F), thickness (T) and weight (W_s). Studies were conducted using 176 eggs laid by 11-month-old quails from a resource population of F_2 crossbreds. The main set of measured and calculated parameters included egg weight (W), volume (V) and surface area (S). In addition, we determined an indicator of elastic shell deformation under a non-destructive load of 0.5 kg ($\delta_{0.5}$). Use of this parameter set allowed us to make the most accurate non-invasive prediction of the values of F ($R = 0.756$), T ($R = 0.266$) and W_s ($R = 0.450$) for quail eggs. As a result of comparative analysis of the current and previously obtained equations for calculating W_s , the disadvantages of using empirical equations were also identified. Herewith, we proposed the so-called *index approach* to forming mathematical dependences, simplifying their further use, e.g., in breeding studies. As such, we selected the following conditionally called indices: *metabolism index* (S/V) and *specific elastic shell deformation* ($\delta_{0.5}/W$). Following the approximation, more convenient and compact dependences were produced. The correlation coefficients between the true and computed values were 0.749 for predicting F , 0.262 for T , and 0.443 for W_s , with corresponding RMSE values equal to 0.416 for F , 0.019 for T , and 0.105 for W_s . The established index representation of empirical equations will serve as a crucial instrument for eggshell quality control and application in quail breeding.

Key words: Japanese quail egg quality, shell quality, shell strength and thickness, shell weight, elastic shell deformation, non-destructive testing technology

Abbreviations and units:

B : egg maximum breadth (cm); d : air cell diameter (cm); D : egg density; D_p : egg diameter; F : shell strength (kg); h : air cell height (cm); L : egg length (cm); R : Pearson correlation coefficient; R^2 : coefficient of determination; S : egg surface area (cm²); S/V : metabolism index (cm²/cm³); T : shell thickness (mm or μ m); V : egg volume (cm³); V_{ac} : air cell volume (cm³); V_s : shell volume (cm³); w : distance of the B axis offset from the egg center (cm); W : egg weight (g); W_s : shell weight (g); δ : elastic shell deformation under the impact of a non-destructive load (mm); $\delta_{0.5}$: elastic shell deformation under a 0.5 kg non-destructive load (mm); $\delta_{0.5}/W$: specific elastic shell deformation (mm/g); δ_{max} : maximum shell deformation at failure (mm).

INTRODUCTION

There is a growing popularity for the consumption of Japanese quail eggs worldwide (Fig. 1) due to their nutritional value (Tunsaringkarn *et al.* 2013; Bayomy *et al.* 2017; Ali & El-Aziz 2019) and profitability (Volkovoy & Bondarenko 1989; Adom *et al.* 2023). It has led the poultry industry to seek knowledge-intensive technological solutions to increase output and quality control. Further advancements in quail breeding and production depend on the development of novel technology for evaluating quail egg quality and other economically important characteristics (e.g., Baumgartner & Bondarenko 1989; Ryabokon *et al.* 2005; Podstreshnyi *et al.* 2010; Podstreshnyi & Tereshchenko 2012a,b; German *et al.* 2022). One of the most significant factors affecting the efficiency of egg production is the shell quality (e.g., Hunton 2005), which is critical to the egg industry due to its impact on both production and food safety. Strong, undamaged eggshells are essential to minimizing losses during egg collection, transportation and processing, and this directly impacts the economics of the poultry industry. Additionally, eggshells play an important role in preventing microbial contamination, ensuring the food safety of the egg contents by acting as a natural barrier to bacteria.

The main quantitative factors by which one can judge the quality of a shell can be characterized as follows: (i) the thickness of the shell and/or its weight; (ii) shell strength, and (iii) shell deformation (e.g., Ketelaere De, 2004; Dunn, 2004; Bain, 2005; Solomon, 2010). Control of shell quality has been thoroughly investigated for chicken eggs (e.g., Ketta & Tůmová 2016). The nuances pertaining to quail eggs, however, compel us revisit the results of many studies obtained for eggs of other species (e.g., Hunton 2005; Trnka *et al.* 2012; Ketta & Tůmová 2016; Narushin *et al.* 2022). In view of this, we explored and sought to understand

how exactly these specific features of quail eggs manifest themselves.

Rahn and Paganelli (1989), based on data from 3217 eggs of extant non-passerine species and subspecies, derived several allometric functions, i.e., dependences on egg weight (W) that characterize the parameters of their shell, of which we will consider here its thickness (T) and weight (W_s):

$$T = 0.0546W^{0.441}, \quad (1)$$

$$W_s = 0.0524W^{1.113}, \quad (2)$$

in which T is measured in mm, and W_s and W in g.

If we recalculate these parameters (Eqs. 1 and 2) for a conventional quail egg weighing 10 to 12 g (e.g., Wilkanowska & Kokoszyński 2012), we obtain variations in the values of $T = 0.15...0.16$ mm, and those of $W_s = 0.68...0.83$ g. However, this is far from the actual measurements in nature as morphometric studies of quail eggs of the above weight demonstrated shell parameter values at the level of $T = 0.21...0.22$ mm, and $W_s = 0.9...1.0$ g (Wilkanowska & Kokoszyński 2012). That is, quail eggs have their own distinctive peculiarities that consistently fall out of the general range of characteristics typical to most bird eggs. In other words, their shell indicators turn out to be 25-40% higher than predicted. By contrast, the validation of Eqs. 1 and 2 as applied to an average chicken egg weighing 60 g resulted in the mean values of $T = 0.33$ mm and $W_s = 5.0$ g that are consistent with the actual ones (e.g., Romanoff & Romanoff 1949).

A similar situation is observed with another important parameter characterizing the quality of the shell – its strength (F). Ar *et al.* (1979), using a much smaller sampling of eggs ($n = 200$) that, nevertheless, covered 47 species from 26 families and 11 orders of birds, derived an allometric dependence for F as follows:

$$F = 50.86W^{0.915}, \quad (3)$$

where F and W are measured in g.

After substituting the same values of $W = 10...12$ g into Eq. 3, we obtain the result of the quail eggshell strength at the level of $F = 0.4...0.5$ kg. However, according to Buchar *et al.* (2015) who studied this parameter in quails, the shell strength (F) value was in the range of 0.7...1.1 kg that exceeds the calculated predicted value by more than twofold. It should be noted that the calculation of the predicted shell strength (Eq. 3) of a standard chicken egg weighing 60 g gives the result of $F = 2.2$ kg; this is lower than the actual values reported in several publications (e.g., Narushin *et al.* 2004, 2021b; Macleod *et al.* 2006; Trnka *et al.* 2012).

Thus, an automatic transfer to quail eggs of parameter relationships known for both chicken eggs and some other average dependences is incorrect. This problem may arise when using non-destructive methods for predicting shell parameters. Indeed, these assessment methods are often empirical in nature, and what was quite adequate for the shell of chicken eggs turns out to be of limited use for other bird species, specifically quails. While it would be easy to estimate the shell quality using destructive methods, especially if this concerns unfertilized food-grade eggs, a non-destructive prediction is essential to assess hatching eggs. Careful and scrupulous development of these non-invasive methods for shell parameters of hatching quail eggs includes several significant aspects of their subsequent practical

application as follows:

1. *Development of technological methods for pre-incubation sorting.* The results of experiments by Ergun and Yamak (2017) suggest that the hatchability of quails from eggs with thicker shells was slightly higher than in other groups, although the differences were insignificant. Analysis of the incubation time using the eggs of 447 avian species (Narushin *et al.* 2024c) showed that the incubation period of bird eggs is affected by the ratio of the shell thickness to its surface area (T/S). Thus, by determining the T value before setting eggs into the incubator, it would be possible to develop various technological solutions for their most effective incubation in terms of energy saving and egg hatchability.
2. *Implementation of selection and genetic measures for various crosses aimed at increasing F .* To study the relationship between the morphological, physical, geometric and other characteristics of the egg and F , examination of shell properties should be carried out using non-destructive technologies. Eggs with most "successful" parameters should subsequently be incubated to pass on the required genes to the next generations.
3. *Improving production efficiency.* Non-destructive testing methods allow manufacturers to verify the quality of products at different stages of production line, identify defects at early stages and prevent defective eggs from reaching the consumer. Timely non-destructive testing allows optimizing production processes and identifying problem areas and risk zones, which helps to increase overall efficiency.

In general, non-destructive testing of eggshell quality is a complex task requiring the use of modern technologies and methods to ensure safety and high quality of products. Given that, compared to chicken, the volume of quail egg production is low, many enterprises are not able to provide sufficiently complex technological solutions, such as NIR spectroscopy (e.g.,

Ahmed et al., 2025). In this regard, calculation methods based on conventional measurements of geometric and/or physical parameters of the egg are preferable. We could apply similar principles established during the studies using chicken eggs to quails. If we do, then among the shell parameters characterizing F (in addition to T), there may also be W_s , or some of its derivatives that require further examination. These may include its ratio to the surface area (W_s/S ; Tyler & Geake 1961) or to the weight of the entire egg (W_s/W ; e.g., Narushin *et al.* 2004) that need further examination. Based on the physical shell properties, the shell strength (F) can be predicted successfully using the magnitude of its elastic deformation (δ) under the impact of a non-destructive load (e.g., Voisey 1975; Voisey & Hamilton 1976; Voisey & MacDonald 1978; Narushin *et al.* 2021b).

With the above in mind, the objective of this research was to develop methods for the non-destructive assessment of the quality of quail eggshells, namely, T , W_s and F , based on the geometric and physical egg properties and parameters, including δ . This non-invasive methodology is crucial for controlling shell quality in zoological research and poultry production practice.

MATERIALS AND METHODS

To achieve the above, 176 eggs were sampled from F_2 quails aged 11 months that originated from a model resource population generated by interbreeding of layer (of Japanese breed) and meat (of Texas breed) types (German *et al.* 2022, 2023; Prituzhalova *et al.* 2023; Volkova *et al.* 2023). Using laboratory electronic scales, each egg was weighed (W) with an

accuracy of 0.01 g. Using a caliper, the egg length (L) and maximum breadth (B) were measured with an accuracy of 0.1 mm. All eggs were photographed (according to Narushin *et al.* 2020a), and the L and B values, as well as the distance w of the B axis offset from the egg center (Narushin *et al.* 2020b) and the egg diameter (D_p) at the distance of $L/4$ from the pointed end (Narushin *et al.* 2021a) were identified using egg images and Microsoft Picture Manager software with an accuracy of 1 pixel. Knowing the size of L in mm and pixels, respectively, the other geometric parameters, i.e., B , w and D_p , were converted to the metric system of measurement.

The egg volume (V) and S were calculated using the following universal formulae previously derived and tested for their adequacy using, among other species, quail eggs (Narushin *et al.* 2024b):

$$V = \frac{\pi}{128} \left[\left(8.917 - 29.998 \frac{w}{L} \right) \left(\frac{D_p}{B} \right)^2 + \left(2.459 + 88.647 \frac{w}{L} \right) \frac{D_p}{B} - 36.26 \frac{w}{L} + 12.453 \right] LB^2, \quad (4)$$

$$S = \pi BL \left(0.389 + 0.188 \frac{B}{L} - 0.063 \frac{w}{L} + 0.365 \frac{D_p}{B} + 0.114 \frac{D_p}{L} - 0.168 \frac{w}{L} \cdot \frac{B}{L} + 0.46 \frac{w}{L} \cdot \frac{D_p}{B} + 0.484 \frac{w}{L} \cdot \frac{D_p}{L} \right), \quad (5)$$

in which all geometric variables are in cm, V is in cm^3 and S is in cm^2 .

The egg density (D) was calculated as the ratio of W to V .

Using the Egg Quality Testing System measuring complex (Stable Micro Systems, Godalming, Surrey, UK), shell strength (F) was measured with an accuracy of 0.001 kg and the degree of its maximum deformation at failure ($\delta_{\max}$) with an accuracy of 0.01 mm. Since the process of shell deformation under loading is linear, as evidenced by both the information from Stable Micro Systems (2022) and the publications of other authors who carried out

similar measurements of quail eggs (Polat *et al.* 2007; Hassan & Geasa 2022), the shell deformation ($\delta_{0.5}$) caused by a non-destructive load of 0.5 kg was recalculated using a formula reflecting the linear dependence of $\delta_{\max}$ on F :

$$\delta_{0.5} = \frac{\delta_{\max}}{2F}, \quad (6)$$

where $\delta_{0.5}$ and $\delta_{\max}$ are measured in mm, and F in kg.

The shell of a broken egg was thoroughly washed from the remaining contents, without separating the subshell membrane. It was then air dried for 24 hours and weighed (W_s) to within an accuracy of 0.01 g. Using a micrometer included in the laboratory equipment of Egg Quality Testing System (Stable Micro Systems), T was measured at three points, i.e., near the egg equator, the pointed and blunt ends, after which the value was averaged.

The shell volume (V_s) was calculated using a previously derived formula (Narushin *et al.* 2024d), taking into account the measured geometric parameters and T :

$$\begin{aligned} V_s = 4T \{ & 0.11 [D_p^2 + 2(L - 3.361w - 2T)(D_p - T)] \\ & + 0.03 [BD_p + (L + 36.267w - 2T)(B + D_p - 2T)] \\ & + 0.153 [B^2 + 2(L - 2.908w - 2T)(B - T)] \} \end{aligned} \quad (7)$$

in which V_s is measured in cm^3 , and all other variables in cm.

Since one of the criteria reflecting F can be the shell porosity, we included in the experiment a stage for determining the air cell volume (V_{ac}), as a possible indirect indicator of porosity. The V_{ac} value (in cm^3) was calculated using a previously deduced formula (Narushin *et al.* 2021c):

$$V_{ac} = \frac{1.32B^2h}{L^3} [h(L^2 + 3.79Lw - 4.08w^2) + 0.012L(L^2 - 5.92Lw + 172.58w^2)], \quad (8)$$

where h is the height of the air cell; all geometric dimensions of the egg are used in cm.

Due to the difficulty of accurately measuring h , its value was calculated based on the dimensions of the air cell diameter (d) using the previously derived formula from Narushin *et al.* (2021c):

$$h = \frac{LB^2 - 2d^2w - \sqrt{(2d^2w - LB^2)^2 - d^2B^2(L - 2w)^2}}{2B^2}. \quad (9)$$

Direct measurements of the d value were performed using a caliper (Fig. 2), with an accuracy of 0.1 mm.

The measured geometric parameters of a quail egg are conventionally presented in Fig. 3.

Several statistical and mathematical procedures that can be found in the STATISTICA 5.5 program (StatSoft, Inc./TIBCO, Palo Alto, CA, USA) and applications for the Microsoft Excel program were used to process the data. Here, the Pearson correlation coefficient (R) and regression models employing the coefficient of determination (R^2) were used to evaluate the validity of the determined associations, with significance being confirmed at the $p < 0.05$ level. To assess the error in calculating the approximated equations, the Root Mean Square Error (RMSE) value was used (e.g., Shi *et al.*, 2020).

To check the adequacy of the approximation equations obtained from the experimental results, we used the holdout method. This approach is the most basic type of cross-validation. As a result, the data set is divided into two groups, referred to as the testing set and the

training set. The function approximator only uses the training set to fit a function. We decided to implement such a test using a double approach, when (i) eggs from the same experimental flock, laid in the same period as those studied, are used, which, however, were not involved in processing the results and deriving the corresponding empirical dependencies; and (ii) by using a sample of eggs laid at a different time, by a different flock, kept in different conditions. For the purpose (i), we selected an additional 10 quail eggs from the same flock and performed similar measurements of the above parameters. The data obtained from these 10 eggs were not used in the approximation process; that is, they were used only as a verification test. For the purpose (ii), we selected eggs of quails of the Japanese breed and of the Texas White breed, which were used to create an F_2 quail resource population. Female of both breeds were kept separately in multi-tiered cages with separate 22.5×40 cm compartments (each bird occupying 900 cm^2). All laying quails were kept under the same conditions: 16 hours of moderate artificial lighting, a temperature range of 20 to 25°C , unrestricted access to nipple drinkers, and full commercial feed for productive quails, which contains 18% crude protein and 2900 kcal/kg of metabolizable energy. A total of 98 eggs were selected, of which 74 were from the Japanese breed and 24 from the Texas White breed. The procedure for analyzing the eggs selected for cross-validation was identical to the experimental group of eggs described above.

RESULTS AND DISCUSSION

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

Shell strength

Such parameter as shell strength (F) has always attracted the greatest interest of researchers and practitioners, as it is directly related to the economic losses of the egg industry. As a result of the correlation analysis, we found that the best option for a non-destructive prediction of the shell strength (F) value can be achieved by using the elastic shell deformation method. As an acceptable load that does not result in a destructive effect for quail eggshells, we set 0.5 kg. The results of this experimental procedure confirmed the adequacy of this load setting, as well as the effectiveness of the F prediction by recording the shell deformation values at $\delta_{0.5}$. The correlation value between these parameters was -0.514 ($p < 0.05$). At the same time, the relationship between F and $\delta_{0.5}$ was hyperbolic (Fig. 4), and the trend line (shown in yellow in Fig. 4) was approximated by the following equation:

$$F = \frac{0.156}{\delta_{0.5}}, \quad (10)$$

in which F is measured in kg, and $\delta_{0.5}$ in mm.

The use of a hyperbola (Eq. 10) to describe the dependence $F = f(\delta_{0.5})$ enabled to increase the prediction accuracy to $R = -0.706$ ($p < 0.05$), and, accordingly, the determination coefficient to $R^2 = 0.498$, with RMSE = 0.450.

Other shell parameters had, although significant, a much more modest relationship with F :

- T ($R = 0.231, p < 0.05$);
- W_s ($R = 0.282, p < 0.05$);
- ratio W_s/S ($R = 0.228, p < 0.05$);

- percentage of shell in the weight of the whole egg, W_s/W ($R = 0.178$, $p < 0.05$).

Of the single parameters that could be determined non-invasively, i.e., while maintaining the integrity of the egg, none demonstrated a significant relationship with the shell strength (F) value. We did, however, have our positive experience in the synergistic effect of a similar F prediction for chicken eggs when using the values of the egg's W , V and/or S separately or in addition to the δ value (Narushin *et al.* 1995, 2004; Narushin 1998, 2001). We thus attempted to apply the same approach to quail eggs. As a result, the following calculative equation was obtained:

$$F = \frac{0.000005W^{0.294}S^{4.542}}{\delta_{0.5}^{1.704}V^{2.72}}, \quad (11)$$

where F is measured in kg, $\delta_{0.5}$ in mm, W in g, V in cm³, and S in cm².

Eq. 11 made it possible somewhat to improve the prediction of the shell strength (F) value to $R^2 = 0.572$ with RMSE = 0.412 and, therefore, can be taken as a basis for practical use, i.e., for both research and industrial applications.

Shell thickness

Unlike F , the prediction of the T value depending on $\delta_{0.5}$ was quite inaccurate, as evidenced by a rather low, although significant, correlation coefficient ($R = -0.158$, $p < 0.05$). While the obtained data could, with some degree of assumption, be described by a power dependence (Fig. 5), the approximated formula was far from being suitable for its practical application:

$$T = \frac{0.221}{\delta_{0.5}^{0.051}}, \quad (12)$$

with $R^2 = 0.035$, $p < 0.05$,

in which T and $\delta_{0.5}$ are measured in mm.

Eq. 12 conformed to the trend line shown in pink in Fig. 5.

The scatter of T parameters relative to the trend line was so large that a more or less accurate prediction was impossible. In this regard, we tried to improve the accuracy of the T prediction by introducing other egg parameters into the calculation. Interestingly, the correlation between T and V , as well as between T and S , was not significant (with $R = 0.146$ and $R = 0.142$, respectively). However, when analyzing the ratio of these parameters (S/V), the absolute value of the correlation coefficient increased and was significant ($R = -0.175$, $p < 0.05$).

In a series of studies from our previous works (Narushin *et al.* 2024c,d,e,f), we suggested that the S/V ratio of bird eggs can characterize the level of their embryonic metabolism. At the same time, T also affects the metabolism of the developing embryo. Because of that, it can be assumed that the maternal body can somehow influence the relationship between the T and S/V values during egg formation. In this respect, in the set of parameters affecting the calculation of T , we decided to use the S/V ratio, instead of individual S and V values. As a result, the following mathematical expression was obtained:

$$T = \frac{0.403}{\delta_{0.5}^{0.054} W^{0.061} \left(\frac{S}{V} \right)^{0.578}}, \quad (13)$$

where T and $\delta_{0.5}$ are measured in mm, W in g, S/V in cm^2/cm^3 .

The correlation between the calculated T values (Eq. 13) and the true ones was 0.266 and, accordingly, was significant ($p < 0.05$). The value of RMSE was equal to 0.019. The accuracy of this prediction, although it was higher than when using only the $\delta_{0.5}$ value (Eq. 1), was clearly insufficient for practical application. Nevertheless, the relationship between various egg parameters and T can be very interesting from the viewpoint of the developmental physiology of embryos inside quail eggs. Considering the peculiarities of the morphological structure of quail eggs, in particular, the already noted disproportionately thick shell relative to the size of the entire egg, the use of Eq. 13 for non-destructive calculation of T will significantly facilitate the study of the physiology of embryonic development. Indeed, the shell is an important factor on which the egg integrity, gas exchange, and the consumption of calcium and some other microelements during embryonic development depend. In this regard, the T/S ratio may be of special interest. We have already mentioned above that the value of this index has an inverse relationship with the duration of incubation of bird eggs (Narushin *et al.* 2024c). Therefore, a relatively accurate T/S prediction may be extremely relevant in studies on the synchronization of quail hatching in an incubator. Therefore, we decided to pay close attention to the method of calculating the T/S value.

Correlation analysis revealed that the highest significant T/S correlation was observed relative to W ($R = -0.556$, $p < 0.05$), V ($R = -0.578$, $p < 0.05$) and S ($R = -0.589$, $p < 0.05$). Although the $\delta_{0.5}$ value showed a rather low and insignificant correlation ($R = -0.107$), it was decided, however, to include it in the prediction. As a result of mathematical processing, the following calculation equation was produced:

$$\frac{T}{S} = \frac{1675.808W^{0.079}V^{1.096}}{\delta_{0.5}^{0.048}S^{2.522}}, \quad (14)$$

in which T/S is measured in $\mu\text{m}/\text{cm}^2$, $\delta_{0.5}$ in mm, W in g, V in cm^3 , and S in cm^2 .

In Eq. 14, the T values were used in μm instead of mm, as before. This is because when deriving empirical equations, which Eq. 14 belongs to, it is important that the values of the variable parameters are in a relatively equal range (scale). This is important because when constructing an empirical dependence, the variable with large values will dominate the calculations (e.g., Seber and Lee, 2003; Montgomery et al., 2012; Myers et al., 2016). This can distort the weight of other variables and lead to an inadequate model. When the parameters are on different scales, it is difficult to compare which variable has a greater influence on the result. Bringing to equal scales allows one to assess the significance of factors correctly. Also, the use of more or less aligned values helps simplify the visual analysis. When analyzing graphs and response surfaces, it is convenient if the variables make a contribution of approximately the same level. This simplifies the perception of observed patterns.

The correlation between the computed T/S (Eq. 14) values and the true ones was 0.601 and, accordingly, was significant ($p < 0.05$), with RMSE = 0.829. A graphical visualization of this relationship is shown in Fig. 6. It should be noted that the exclusion of any of the four influencing parameters of the dependence $T/S = f(\delta_{0.5}, W, V, S)$ entailed a decrease in the calculation accuracy. Thus, Eq. 14 can be recommended for practical use when approximately estimating the T/S ratio of quail eggs.

Shell weight

There is one more parameter characterizing the shell properties that is the value of W_s . In our previous study (Narushin *et al.* 2024a) conducted on 54 eggs of the same F₂ quail resource population as in the current research, we proposed a calculation formula for W_s , in which we used three main parameters: W , V and S :

$$W_s = 433.204W^{4.967}V^{-1.038}S^{-4.833}, \quad (15)$$

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

where W_s and W are measured in g, V in cm³, and S in cm².

Therefore, our initial endeavor was to assess the adequacy of the previously derived dependence to the current experimental data. However, the results of the calculation using Eq. 15 showed a significant, but rather low correlation relative to the true W_s values ($R = 0.217$, $p < 0.05$). Obviously, such a discrepancy is caused by the fact that the age of quails in our previous study (Narushin *et al.* 2024a) was 2–3 months, and hens in the current investigation were 11-month-old. There have been several previous research reports pointing out differences in the morphology of quail eggs in relation to changes in the age of laying hens (e.g., Corrêa *et al.* 2012; Zita *et al.* 2013; Santos *et al.* 2015), which may have caused such discrepancies.

We decided to address this issue by approximating the results of the current experiment with a dependence similar to Eq. 15. As a result, the following formula was produced:

$$W_s = 9.412W^{0.521}V^{1.44}S^{-2.212}, \quad (16)$$

in which W_s and W are measured in g, V in cm³, and S in cm².

The results using Eq. 16 gave a higher and more significant correlation with the true W_s values ($R = 0.408$, $p < 0.05$), with $RMSE = 0.107$. Considering our positive experience in improving the above prediction accuracy of other values characterizing the qualitative shell indicators (F and T) when including the $\delta_{0.5}$ value in the calculation, we also decided to test the result of a similar prediction of W_s . As a result, the following equation was derived:

$$W_s = \frac{8.251W^{0.405}V^{1.567}}{\delta_{0.5}^{0.087}S^{2.239}}, \quad (17)$$

where W_s and W are measured in g, $\delta_{0.5}$ in mm, V in cm^3 , and S in cm^2 .

Using Eq. 17, it was possible to increase slightly the correlation coefficient, which amounted to $R = 0.450$ ($p < 0.05$), with $RMSE = 0.104$. Herewith, it should be noted that the single correlation between W_s and $\delta_{0.5}$ was insignificant and low ($R = -0.107$).

Which parameters predict shell characteristics in the best way?

Based on the obtained results of assessing the qualitative characteristics of the quail eggshell, it can be argued that the elastic deformation from the impact of a non-destructive load is a significant additional factor, and, in the case of F , the main factor in these predictions. This approach echoes the studies of chicken eggshells, where it has been known and utilized for more than 60 years (Schoorl & Boersma 1962). Since the higher the value of the non-destructive load, the more accurate the prediction of F (Voisey 1975; Voisey & Hamilton 1976; Voisey & MacDonald 1978), our recommendation is to test the quail eggshells with a load of no greater than 0.5 kg. This limiting safe load value assured the integrity of the eggs and the adequacy of the obtained characteristics of their shell.

As for the use of more than one parameter for the assessment of shell characteristics, the opinions of chicken egg researchers differ somewhat on this issue. For example, the results of Voisey and Hunt (1976), as well as our study (Narushin & Chausovsky 1997), did not show a special effect from the inclusion of several other egg parameters in the F prediction. At the same time, other research data (Narushin & Morgun 1995; Narushin 1997), including the theoretical approach implemented for assessing F (Narushin 1996), testified to the opposite. Regarding a similar issue with relation to quail eggs, it can be stated unequivocally: the use of a set of such parameters as the values of $\delta_{0.5}$, W , V and S , undoubtedly have a positive effect on the results of the prediction of shell characteristics, i.e., F , T and W_s .

The best prediction outcome was obtained by recalculating the shell strength (F) value (Eq. 11), and the worst one by calculating T (Eq. 13). Because the larger the set of parameters involved in the calculation is, the more accurate the result becomes, it is possible that, in order to predict the T value of quail eggs, other non-destructive measurements should be used. These include, for example, the ultrasonic method for assessing T (ORKA 2020). Ergun and Yamak (2017) successfully tested the applicability of using this device on quail eggs.

As revealed by the experience of comparative application of the previously derived calculation equation for W_s using a different sampling of eggs, the implementation of empirical formulae is adequate only for the data that served as the basis for deriving this formula. Hereby, the mathematical analysis we conducted when computing the indicators F , T (and/or T/S) and W_s is to a greater extent an example of a methodical approach that can be successfully applied in delivering formulae for non-destructive determination of quail egg parameters. Subsequently, the produced mathematical equations can be successfully used for

eggs obtained from quails of the same population and age group and under identical feeding and maintenance conditions.

Predicting ability of indices

The convenience of extensive use of such an approach naturally raises some doubts about its wider applicability. After all, the examination of each new group of eggs should be started from scratch, i.e., from analyzing the egg morphology of this group and then approximating the shell parameters with a new, refined expression. In addition, this expression will be adequate only for that specific sampling. We tried to simplify this somewhat by transforming the obtained Eqs. 11, 13 and 17 into the so-called *index form*. We have previously used this type of mathematical transformation in studies of the mathematical description of the geometry of bird eggs (e.g., Narushin *et al.* 2021a, 2023, 2024a). In this case, a combination of certain parameters forms definite indices, the values of which are much less variable than the parameters included in them. For example, in our Eq. 13 design, we used the S/V ratio, which can be considered as a geometric index that also has physiological meaning through assessing potentially the level of embryonic metabolism (e.g., Narushin *et al.* 2024d,e,f).

Analyzing Eqs. 11, 13 and 17, we noted that, mathematically, all the parameters of the equation can be easily combined in the form of the following ratios: S/V , W/V and $\delta_{0.5}/W$. The S/V index we have already considered can be interpreted as the level of embryo metabolism. The W/V ratio is nothing more than D . The third ratio, i.e., $\delta_{0.5}/W$, can be conditionally called the *specific elastic shell deformation*. Checking the correlation level between each of the shell quality indicators (F , T and W_s) relative to the above indices demonstrated extremely low and

insignificant coefficients of correlation with W/V (i.e., D). Considering that the W and V parameters included in D are also present in the S/V and $\delta_{0.5}/W$ indices, we decided to exclude the D values from the approximation process of the calculation equations. As a result, the following formulae were proposed instead of Eqs. 11, 13 and 17:

$$F = 0.000076 \frac{\left(\frac{S}{V}\right)^{2.746}}{\left(\frac{\delta_{0.5}}{W}\right)^{1.62}}, \quad (18)$$

$$T = \frac{0.244}{\left(\frac{\delta_{0.5}}{W}\right)^{0.051} \left(\frac{S}{V}\right)^{0.279}}, \quad (19)$$

$$W_s = \frac{1.499}{\left(\frac{\delta_{0.5}}{W}\right)^{0.092} \left(\frac{S}{V}\right)^{1.128}}. \quad (20)$$

The parameters included in Eqs. 18, 19 and 20 have the same dimensions as in Eqs. 11, 13 and 17. The correlation coefficients between the computed and true parameters were practically no different from those obtained for Eqs. 11, 13 and 17, and were: 0.749 for Eq. 18, 0.262 for Eq. 19, and 0.443 for Eq. 20. Correspondingly, the values of RMSE were 0.416 for Eq. 18, 0.019 for Eq. 19, and 0.105 for Eq. 20.

The adequacy of the obtained calculation equations for F , T and W_s (i.e., Eqs. 18–20, respectively), when using them relative to eggs not included in the analyzed sample, was tested using the cross-validation holdout method, considering the parameters of 10 additionally measured eggs. The use of approximation formulae (18)–(20) demonstrated the following results: calculation of F (Eq. 18), $R = 0.703$, RMSE = 0.418; T (Eq. 19), $R = 0.150$, RMSE = 0.019; and W_s (Eq. 20), $R = 0.551$, RMSE = 0.115. That is, the accuracy indicators of the

obtained calculation data of eggs of the same experimental group of quails are extremely close to the predicted values for the egg sample, based on which these calculation equations were derived.

A similar test of empirical equations (18)–(20) on a sample of 98 quail eggs of the Japanese and Texas White breeds yielded the following data: calculation of F (Eq. 18), $R = 0.706$, $RMSE = 0.571$; T (Eq. 19), $R = 0.054$, $RMSE = 0.036$; and W_s (Eq. 20), $R = 0.369$, $RMSE = 0.621$. It can be concluded that the results of using Eqs 18–20 demonstrated a fairly similar order of values to those for the eggs of the experimental group, especially for the prediction of shell strength F (Eq. 18). The prediction of W_s (Eq. 20) values was somewhat lower than in the experiment. However, the calculated T value (Eq. 19) was clearly lower with an insignificant value of the correlation coefficient, which casts doubt on the possibility of practical use of the empirical equation (19).

Shell thickness prediction: possible improvements

If the accuracy of the predicted values of F and W_s using the obtained calculation equations (18) and (20) can be considered satisfactory, then this cannot be said about T . That is, the elastic deformation of the shell is not such an informative indicator for the prediction of its shell. It should be noted that the founders of this principle of studying the physical characteristics of the shell, Schoorl and Boersma (1962), demonstrated that the greatest correlation was obtained between deformation and percentage shell and the least one with the strength of the chicken egg. Some explanation for the factor of low prediction of the T value of quail eggs in comparison with chicken eggs may lie in the structural and physical differences in the shell of these species. We have already mentioned in the Introduction section about such deviations from the average values of the trend line derived from the data

of the entire variety of bird eggs. If to assess the strength of the shell and its weight, which is already important for commercial quail farming, it is sufficient to measure and/or calculate the main non-destructive parameters of the egg, i.e., $\delta_{0.5}$, W , V and S , then to predict the thickness of the shell, this number of parameters is not enough. Perhaps it is advisable to add ultrasonic diagnostics of the shell, e.g., commercially available apparatuses for testing shell thickness, like the ultrasonic device by ORKA (2020). Ergun and Yamak (2017) successfully tested the applicability of using this device to examine quail eggs. Nevertheless, despite the insufficiently accurate prediction of the T value, the fact of its dependence on the S/V and $\delta_{0.5}/W$ indices remains undeniable, which can be used in breeding practice.

Ways of practical use of indexes

The index representation of empirical dependences has a clear advantage over conventional parametric empirical equations. This is because it is much easier to evaluate analytically and draw corresponding conclusions. It also simplifies the subsequent practical work of breeders who concentrate their further research on changing the combination of several interrelated parameters. As an example, consider a scenario of a possible analytical procedure using Eq. 18. Suppose we are faced with the task of increasing F : Based on the obtained mathematical dependence, we should increase the value of the numerator and, accordingly, decrease the value of the denominator. To do this, the metabolic index (S/V) should be increased, and, according to our previous research (Narushin *et al.* 2024e), this can be done by giving the egg a more elongated, conical shape. At the same time, the specific elastic shell deformation ($\delta_{0.5}/W$) should be reduced, which can be done by increasing W , along with a relatively low value of $\delta_{0.5}$. Thus, the breeder already has some initial settings and potential selection traits for further work towards increasing F .

Somewhat unexpectedly, at first glance, there was an absence of any significant correlation between the size of the air cell and the shell parameters. This was associated with the fact that we studied fresh eggs that were analyzed almost immediately after they were laid. In our investigation, V_{ac} was less than 1% of the total egg volume (Table 1), and the variations of this parameter within the studied group did not allow us to identify its relationship with the studied shell parameters. Perhaps this indicator can be excluded from the analysis when conducting similar studies on freshly laid quail eggs.

CONCLUSIONS

Based on the performed Japanese quail eggshell quality experiments using non-destructive testing technology and analysis of the obtained research results, the following conclusions can be drawn:

1. The method of recording the value of elastic shell deformation due to a non-destructive load of 0.5 kg ($\delta_{0.5}$) can be used successfully to predict such quality characteristics of the quail eggshell as its F , T and W_s .
2. The prediction accuracy can be significantly improved by introducing into the calculation, in addition to the value of $\delta_{0.5}$, other parameters of the egg: W , V and S . As a result of deriving empirical dependences based on the obtained experimental data, the correlation coefficients between the true and computed parameters were significant and amounted to 0.756 for F (Eq. 11), 0.266 for T (Eq. 13), and 0.450 for W_s (Eq. 17).
3. As indices, with the help of which it is possible to approximate mathematical dependences

for calculating the shell parameters (F , T and W_s), we proposed the following, conventionally called, metabolic index (S/V) and specific elastic shell deformation ($\delta_{0.5}/W$). After approximation, more convenient and compact dependences were derived (Eqs. 18, 19 and 20). Herewith, the correlation coefficients between the true and calculated values practically did not differ from the parametric equations (Eqs. 11, 13 and 17) and amounted to 0.749 for F (Eq. 18), 0.262 for T (Eq. 19) and 0.443 for W_s (Eq. 20). The developed mechanism of index representation of empirical equations is a more universal and convenient tool for their analysis and further use in zoology (oology), quail breeding studies, and practical control of shell quality properties.

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AUTHOR CONTRIBUTIONS

Valeriy G. Narushin contributed to conceptualization, data curation, formal analysis, investigation, methodology, resources, software, visualization, writing – original draft, and writing – review & editing. Natalia A. Volkova took part in data curation, funding acquisition, investigation, methodology, project administration, supervision, validation, and writing – review & editing. Alan Yu. Dzhagaev participated in investigation, validation, and visualization.

Zarina V. Gagieva was involved in investigation. Ludmila A. Volkova contributed to investigation, and validation. Darren K. Griffin provided supervision, and writing – review & editing. Michael N. Romanov took part in project administration, validation, visualization, writing – original draft, and writing – review & editing. Natalia A. Zinovieva contributed to funding acquisition, project administration, supervision, and writing – review & editing. All authors have read and approved the final version of the manuscript.

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Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interest disclosure

The authors declare no conflicts of interest.

REFERENCES

Adom, E., Bir, C. and Lambert, L.H. (2023) A financial comparison of small-scale quail and laying hen farm enterprises. *Poult. Sci.* **102**, 102507.
<https://doi.org/10.1016/j.psj.2023.102507>

- Ahmed, M.W., Alam, S., Khaliduzzaman, A., Emmert, J.L. and Kamruzzaman, M. (2025) Non-destructive measurement of eggshell strength using NIR spectroscopy and explainable artificial intelligence. *J. Sci. Food Agric.* **105**, 5550–5562. <https://doi.org/10.1002/jsfa.14290>
- Ali, M.A. and El-Aziz, A.A.A. (2019) Comparative study on nutritional value of quail and chicken eggs. *J. Res. Fields Spec. Educ.* **15**, 39–35. <https://doi.org/10.21608/jedu.2019.73533>
- Ar, A., Rahn, H. and Paganelli, C.V. (1979) The avian egg: mass and strength. *Condor* **81**, 331–337. <https://doi.org/10.2307/1366955>
- Bain, M.M. (2005) Recent advances in the assessment of eggshell quality and their future application. *Worlds Poult. Sci. J.* **61**, 268–277. <https://doi.org/10.1079/WPS200459>
- Baumgartner, J. and Bondarenko, Yu.V. (1989) Search for autosexing strains and crosses in Japanese quail. *In* Proceedings of the 8th International Symposium on Actual Problems of Avian Genetics. Slovak Society for Agriculture, Forestry, Food and Veterinary Sciences of Slovak Academy of Sciences; Poultry Research and Production Institute Bratislava; Czechoslovak Branch of WPSA, Smolenice, Czechoslovakia, pp. 262–265. <https://www.cabidigitallibrary.org/doi/full/10.5555/19890171986> (accessed 18 March 2025).
- Bayomy, H.M., Rozan, M.A. and Mohammed, G.M. (2017) Nutritional composition of quail meatballs and quail pickled eggs. *J. Nutr. Food Sci.* **7**, 1–5. <https://doi.org/10.4172/2155-9600.1000584>
- Buchar, J., Nedomova, S., Trnka, J. and Strnkova, J. (2015) Behaviour of Japanese quail eggs under mechanical compression. *Int. J. Food Prop.* **18**, 1110–1118. <https://doi.org/10.1080/10942912.2013.862634>

- Corrêa, A.B., Silva, M.A., Corrêa, G.S.S., Santos, G.G., Wenceslau, R.R. and Felipe, V.P.S. (2012) Desempenho de codornas de corte oriundas de diferentes classes de idades da matriz e de peso dos ovos. *Arq. Bras. Med. Vet. Zootec.* **64**, 380–388. <https://doi.org/10.1590/S0102-09352012000200018>
- De Ketelaere, B., Bamelis, F., Kemps, B., Decuypere, E. and De Baerdemaeker, J. (2004) Non-destructive measurements of the egg quality. *Worlds Poult. Sci. J.* **60**, 289–302. <https://doi.org/10.1079/WPS200417>
- Dunn, I.C. (2004) Breeding strategies to improve the egg's natural defence. *Worlds Poult. Sci. J.* **60**, 458–468. <https://doi.org/10.1079/WPS200429>
- Ergun, O.F. and Yamak, U.S. (2017) The effect of eggshell thickness on hatchability of quail eggs. *Vet. World* **10**, 1114–1117. <https://doi.org/10.14202/vetworld.2017.1114-1117>
- German, N.Yu., Volkova, N.A., Larionova, P.V., Vetokh, A.N., Volkova, L.A., Sermyagin, A.A., *et al.* (2022) Genome-wide association studies of growth dynamics in quails *Coturnix coturnix*. *S.-kh. biol. [Agric. Biol.]* **57**, 1136–1146. <https://doi.org/10.15389/agrobiology.2022.6.1136eng>
- German, N.Yu., Vetokh, A.N., Dzhagaev, A.Yu., Ilyina, E.R. and Kotova, T.O. (2023) Morphometric parameters of eggs from breeds quail for meat. *Vetkorm [Vet. Feeding]* **2**, 20–23. <https://doi.org/10.30917/ATT-VK-1814-9588-2023-2-5>
- Hassan, M.H.A. and Geasa, M.M.M. (2022) Determination of mechanical behavior and physical properties of quail eggs. *J. Soil Sci. Agric. Eng.* **13**, 59–63. <https://doi.org/10.21608/jssae.2022.119254.1050>
- Hunton, P. (2005) Research on eggshell structure and quality: an historical overview. *Braz. J. Poult. Sci.* **7**, 67–71. <https://doi.org/10.1590/S1516-635X2005000200001>

- Ketta, M. and Tůmová, E. (2016) Eggshell structure, measurements, and quality-affecting factors in laying hens: a review. *Czech J. Anim. Sci.* **61**, 299–309. <https://doi.org/10.17221/46/2015-CJAS>
- Macleod, N., Bain, M.M. and Hancock, J.W. (2006) The mechanics and mechanisms of failure of hens' eggs. *Int. J. Fract.* **142**, 29–41. <https://doi.org/10.1007/s10704-006-9018-5>
- Montgomery, D.C., Peck, E.A. and Vining, G.G. (2012) *Introduction to Linear Regression Analysis*, Wiley, 5th ed. https://www.kwcsangli.in/uploads/3--Introduction_to_Linear_Regression_Analysis__5th_ed._Douglas_C._Montgomery__Elizabeth_A._Peck__and_G_.pdf
- Myers, R.H., Montgomery, D.C. and Anderson-Cook, C.M. (2016) *Response Surface Methodology: Process and Product Optimization Using Designed Experiments*. Wiley, 4th ed.
- Narushin, V.G. (1996) Method for non-destructive estimation of egg shell quality. *In* *Proceedings of the International Conference on Agricultural Engineering*. European Society of Agricultural Engineers; Hiszpania Ministerio de Agricultura, Pesca y Alimentación; Comisión Española de Ingeniería Rural; Universidad Politécnica de Madrid, Madrid, Spain, pp. 829–830. <https://www.researchgate.net/publication/355807910> (accessed 18 March 2025).
- Narushin, V.G. (1997) Method for non-destructive estimation of strength characteristics in the shells of avian eggs. *In* *Book of Abstracts of the 6th International Conference on Agrophysics*. International Society of Soil Science; Institute of Agrophysics, Polish Academy of Sciences, Lublin, Poland, Vol. 1, p. 116. <https://www.researchgate.net/publication/355808130> (accessed 18 March 2025).

- Narushin, V.G. (1998) Shell strength as an indicator of egg quality: methods for estimation. *In* Proceedings and Abstracts of the 10th European Poultry Conference “The Poultry Industry Towards the 21st Century”. World’s Poultry Science Association, Jerusalem, Israel, Vol. 2, pp. 684–687. <https://www.researchgate.net/publication/330289728> (accessed 18 March 2025).
- Narushin, V.G. (2001) What egg parameters predict best its shell strength? *In* Proceedings of the 9th European Symposium on the Quality of Eggs and Egg Products (eds. Mulder, R.W.A.W. and Bilgili, S.F.). WPSA Turkish Branch, Kuşadası, Turkey, pp. 349–355. <https://www.researchgate.net/publication/330289655> (accessed 18 March 2025).
- Narushin, V.G. and Chausovsky, G.A. (1997) Improved method and techniques for measuring the elastic deformation in thin-walled casings. *In* Proceedings of the International Conference on Experimental Model Research and Testing of Thin-walled Structures (eds. Drdácáký, M. and Peköz, T.). Academy of Sciences of the Czech Republic, Institute of Theoretical and Applied Mechanics, Prague, Czech Republic, pp. 79–82. <https://www.researchgate.net/publication/355808269> (accessed 18 March 2025).
- Narushin, V.G. and Morgun, A.Y. (1995) Shell deformation in research of egg strength. *In* Proceedings of the 11th International Symposium “Current Problems in Avian Genetics”. World’s Poultry Science Association, Polish Branch, Balice near Kraków, Poland, pp. 164–166. <https://www.researchgate.net/publication/355808089> (accessed 18 March 2025).
- Narushin, V.G., van Kempen, T.A., Wineland, M.J. and Christensen, V.L. (2004) Comparing infrared spectroscopy and egg size measurements for predicting eggshell quality. *Biosyst. Eng.* **87**, 101–107. <https://doi.org/10.1016/j.biosystemseng.2003.12.006>

- Narushin, V.G., Lu, G., Cugley, J., Romanov, M.N. and Griffin, D.K. (2020a) A 2-D imaging-assisted geometrical transformation method for non-destructive evaluation of the volume and surface area of avian eggs. *Food Control* **112**, 107112. <https://doi.org/10.1016/j.foodcont.2020.107112>
- Narushin, V.G., Romanov, M.N., Lu, G., Cugley, J. and Griffin, D.K. (2020b) Digital imaging assisted geometry of chicken eggs using Hügelschäffer's model. *Biosyst. Eng.* **197**, 45–55. <https://doi.org/10.1016/j.biosystemseng.2020.06.008>
- Narushin, V.G., Romanov, M.N. and Griffin, D.K. (2021a) Egg and math: introducing a universal formula for egg shape. *Ann. N. Y. Acad. Sci.* **1505**, 169–177. <https://doi.org/10.1111/nyas.14680>
- Narushin, V.G., Chausov, M.G., Shevchenko, L.V., Pylypenko, A.P., Davydovych, V.A., Romanov, M.N. *et al.* (2021b) Shell, a naturally engineered egg packaging: Estimated for strength by non-destructive testing for elastic deformation. *Biosyst. Eng.* **210**, 235–246. <https://doi.org/10.1016/j.biosystemseng.2021.08.023>
- Narushin, V.G., Romanov, M.N. and Griffin, D.K. (2021c) Non-destructive evaluation of the volumes of egg shell and interior: Theoretical approach. *J. Food Eng.* **300**, 110536. <https://doi.org/10.1016/j.jfoodeng.2021.110536>
- Narushin, V.G., Griffin, A.W., Romanov, M.N. and Griffin, D.K. (2022) Measurement of the neutral axis in avian eggshells reveals which species conform to the golden ratio. *Ann. N. Y. Acad. Sci.* **1517**, 143–153. <https://doi.org/10.1111/nyas.14895>
- Narushin, V.G., Orszulik, S.T., Romanov, M.N. and Griffin, D.K. (2023) A novel approach to egg and math: Improved geometrical standardization of any avian egg profile. *Ann. N. Y. Acad. Sci.* **1529**, 61–71. <https://doi.org/10.1111/nyas.15059>

- Narushin, V.G., Volkova, N.A., Vetokh, A.N., Sotnikov, D.A., Volkova, L.A., Griffin, D.K., *et al.* (2024a) 'Eggology' and mathematics of a quail egg: An innovative non-destructive technology for evaluating egg parameters in Japanese quail. *Food Bioprod. Process.* **146**, 49–57. <https://doi.org/10.1016/j.fbp.2024.04.007>
- Narushin, V.G., Volkova, N.A., Vetokh, A.N., Dzhagaev, A.Yu., Sotnikov, D.A., Volkova, L.A., *et al.* (2024b) Reimagining Archimedes: An innovative and accurate calculation of volumes and asserting another standard method for defining the surface area of quail and any avian eggs. *Food Bioprod. Process.* **147**, 327–334. <https://doi.org/10.1016/j.fbp.2024.07.013>
- Narushin, V.G., Romanov, M.N., Avni-Magen, N. and Griffin, D.K. (2024c) Brood parasitism and host-parasite relationships: Cuckoos adapt to reduce the time of hatching ahead of host nestlings by increasing egg thickness. *Int. J. Parasitol. Parasites Wildl.* **25**, 100979. <https://doi.org/10.1016/j.ijppaw.2024.100979>
- Narushin, V.G., Romanov, M.N., Avni-Magen, N. and Griffin, D.K. (2024d) Accurate calculation of the content volume, density and original weight of museum curated eggs. *Sci. Rep.* **14**, 31594. <https://doi.org/10.1038/s41598-024-75397-y>
- Narushin, V.G., Romanov, M.N. and Griffin, D.K. (2024e) Pear-shaped eggs evolved to maximize the surface area-to-volume ratio, increase metabolism, and shorten incubation time in birds. *Integr. Zool.* (online). <https://doi.org/10.1111/1749-4877.12936>
- Narushin, V.G., Romanov, M.N., Avni-Magen, N. and Griffin, D.K. (2024f) Avian egg incubation period: revisiting existing allometric relationships. *Sci. Rep.* (submitted).
- ORKA (2020) Egg Shell Thickness Gauge. ORKA Food Technology Ltd. <https://eggtester.com/eggshell-thickness-gauge> (accessed 18 March 2025).

- Podstreshnyi, O. and Tereshchenko, O. (2012a) [Maintenance of adult quails]. *Ahrar. krayina [Agrar. Country]* **6**, 8–9. <https://www.researchgate.net/publication/342832587> (accessed 18 March 2025).
- Podstreshnyi, O. and Tereshchenko, O. (2012b) [Feeding young quails]. *Ahrar, krayina [Agrar. Country]* **7**, 6. <https://www.researchgate.net/publication/342832583> (accessed 18 March 2025).
- Podstreshnyi, O.P., Tereshchenko, O.V., Katerynych, O.O., Tkachyk, T.E. and Podstreshna, I.O. (2010) [Production of Quail Eggs and Meat: Methodical Recommendations] (ed. Tereshchenko, O.V.), 2nd ed. Poultry Research Institute, NAAS of Ukraine, Birky, Ukraine. <https://www.researchgate.net/publication/342802513> (accessed 18 March 2025).
- Polat R., Tarhan, S., Cetin, M. and Atay, U. (2007) Mechanical behavior under compression loading and some physical parameters of Japanese quail (*Coturnix coturnix japonica*) eggs. *Czech J. Anim. Sci.* **52**, 50–56. <https://doi.org/10.17221/2262-CJAS>
- Prituzhalova, A.O., Volkova, N.A., Kuzmina, T.I., Vetokh, A.N. and Dzhagaev, A.Yu. (2023) Monitoring of indicators of chromatin status in quails ovarian follicles granulosa cells of different directions of productivity. *Agrar. nauka [Agrar. Sci.]* **368**, 53–57. <https://doi.org/10.32634/0869-8155-2023-368-3-53-57>
- Rahn, H. and Paganelli, C.V. (1989) Shell mass, thickness and density of avian eggs derived from the tables of Schönwetter. *J. Ornithol.* **130**, 59–68. <https://doi.org/10.1007/BF01647162>
- Seber, G.A.F. and Lee, A.J. (2003) *Linear Regression Analysis*. Wiley-Interscience, 2nd ed. https://avys.omu.edu.tr/storage/app/public/rezzanu/136403/Linear_Regression_Analysis__2nd_edition__Wiley_Series_in_Probability_and_Statistics_SEBER.pdf
- Romanoff, A.L. and Romanoff, A.J. (1949) *The Avian Egg*. John Wiley & Sons, New York, USA.

- Ryabokon, Yu.O., Pabat, V.O., Mykytyuk, D.M., Frolov, V.V., Katerynych, O.O., Bondarenko, Yu.V., *et al.* (2005) [Catalog of Poultry Breeding Resources of Ukraine] (ed. Ryabokon, Yu.O.). Poultry Research Institute, Kharkiv, Ukraine. <http://avianua.com/archiv/plevreestr/per.pdf> (accessed 18 March 2025).
- Santos, T., Murakami, A., Oliveira, C., Moraes, G., Stefanello, C., Carneiro, T., *et al.* (2015) Influence of European quail breeders age on egg quality, incubation, fertility and progeny performance. *Braz. J. Poult. Sci.* **17**, 49–56. <https://doi.org/10.1590/1516-635x170149-56>
- Schoorl, P. and Boersma, H.Y. (1962) Research on the quality of the egg shell (A new method of determination). *In* Proceedings of the 12th World's Poultry Congress. World's Poultry Science Association, Sidney, Australia, pp. 432–435.
- Shi, P., Ratkowsky, D.A., and Gielis, J. (2020) The generalized gielis geometric equation and its application. *Symmetry* **12**, 645. <https://doi.org/10.3390/sym12040645>
- Solomon, S.E. (2010) The eggshell: strength, structure and function. *Br. Poult. Sci.* **51**(Suppl 1), 52–59. <https://doi.org/10.1080/00071668.2010.497296>
- Stable Micro Systems (2022) Egg Quality Testing System Manual. Version v. 3. <https://www.stablemicrosystems.com/forms/request-manuals-and-user-guides/#:~:text=Egg-,Quality,-Testing%20System%20Manual> (accessed 18 March 2025).
- Trnka, J., Buchar, J., Severa, L., Nedomová, Š. and Stoklasová, P. (2012) Effect of loading rate on hen's eggshell mechanics. *J. Food Res.* **1**, 96–105. <https://doi.org/10.5539/jfr.v1n4p96>
- Tunsaringkarn, T., Tungjaroenchai, W. and Siriwong, W. (2013) Nutrient benefits of quail (*Coturnix coturnix japonica*) eggs. *Int. J. Sci. Res.* **3**, 1–8. https://afst.valahia.ro/wp-content/uploads/2022/09/s01_w02_full_2012.pdf (accessed 18 March 2025).

- Tyler, C. and Geake, F.H. (1961) Studies on egg shells. XV.—critical appraisal of various methods of assessing shell thickness. *J. Sci. Food Agric.* **12**, 281–289. <https://doi.org/10.1002/jsfa.2740120404>
- Voisey, P.W. (1975) Field comparison of two instruments for measuring shell deformation to estimate eggshell strength. *Poult. Sci.* **54**, 190–194. <https://doi.org/10.3382/ps.0540190>
- Voisey, P.W. and Hamilton, R.M.G. (1976) Factors affecting the non-destructive and destructive methods of measuring egg shell strength by the quasi-static compression test. *Br. Poult. Sci.* **17**, 103–124. <https://doi.org/10.1080/00071667608416254>
- Voisey, P.W. and Hunt, J.R. (1976) Comparison of several eggshell characteristics with impact resistance. *Can. J. Anim. Sci.* **56**, 299–304. <https://doi.org/10.4141/cjas76-035>
- Voisey, P.W. and MacDonald, D.C. (1978) Laboratory measurements of eggshell strength. 1. An instrument for measuring shell strength by quasistatic compression, puncture and non-destructive deformation. *Poult. Sci.* **57**, 860–869. <https://doi.org/10.3382/ps.0570860>
- Volkova, N.A., German, N.Y., Larionova, P.V., Vetokh, A.N., Romanov, M.N. and Zinovieva, N.A. (2023) Identification of SNPs and candidate genes associated with abdominal fat deposition in quails (*Coturnix japonica*). *S.-kh. biol. [Agric. Biol.]*, **58**, 1079–1087. <https://doi.org/10.15389/agrobiology.2023.6.1079eng>
- Volkovoy, S. and Bondarenko, Yu. (1989) [Japanese quail plumage rainbow]. *Priusadebnoye khoz-vo [Allot. Husb.]*, **5**, 14–15. <https://yablonka.net/world/zh/686-raduga-opereniya-yaponskogo-perepela.html> (accessed 18 March 2025).
- Wilkanowska, A. and Kokoszyński, D. (2012) Layer age and quality of pharaoh quail eggs. *J. Cent. Eur. Agric.* **13**, 10–21. <https://doi.org/10.5513/JCEA01/13.1.1007>.

Zita, L., Ledvinka, Z. and Klesalová, L. (2013) The effect of the age of Japanese quails on certain egg quality traits and their relationships. Vet. Arh. **83**, 223–232. <https://hrcak.srce.hr/99851> (accessed 18 March 2025).

Table 1. Data on variables for quail eggs that have been measured and computed

Parameters	Mean	Standard deviation
Egg weight, W (g)	11.37	1.14
Length, L (cm)	3.26	0.14
Maximum breadth, B (cm)	2.50	0.09
Egg volume, V (cm ³)	10.39	1.06
Shell surface area, S (cm ²)	22.99	1.56
Egg density, D (g/cm ³)	1.094	0.025
Shell weight, W_s (g)	0.94	0.12
Shell thickness, T (mm)	0.248	0.020
Shell strength, F (kg)	1.62	0.62
Shell maximum deformation, $\delta_{\max}$ (mm)	0.31	0.09
Air cell volume, V_{ac} (cm ³)	0.07	0.04

Figure Legends

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

Fig. 2. Measuring the air cell diameter (d).

Fig. 3. Scheme of measuring linear parameters of a quail egg.

Fig. 4. Graphic dependence of the shell strength (F) on the value of its deformation ($\delta_{0.5}$) under the impact of a non-destructive load of 0.5 kg.

Fig. 5. Graphic dependence of the shell thickness (T) on the value of its deformation ($\delta_{0.5}$) under the impact of a non-destructive load of 0.5 kg.

Fig. 6. Graphical visualization of the relationship between the true (vertical axis) and calculated (according to Eq. 14; horizontal axis) values of T/S .