Size Distribution of Barley Kernels

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Abstract

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Barley primarily serves as a major animal feed crop; smaller amounts of barley are used in health foods and in the malting process. Detailed geometric parameters of kernels are very important for the design of food engineering processes, such as the air transport, drying, milling, and malting. Image analysis was used to determine the size parameters of one hundred kernels of selected varieties of *Hordeum vulgare* L. The data for every kernel captured were stored for further use, together with the mean, standard deviation (SD), coefficient of variation (*CV*), and images themselves. The measured data were then used to compute the volume and surface area of each of the five kernel models (Models 0–4), the results being subsequently verified by pycnometric measurement. Model 0 represents the general ellipsoid, models 1–3 various combinations of two parts of a general ellipsoid with one or two cone frustums. The best fitted model 4 was a combination of two cone frustums. Based on the results of image analysis measurements and on the presented model 4, a simplified method for the specific surface estimation of barley grains from the weight of 1000 kernels is recommended.

Keywords: digital image analysis; specific surface area; barley; kernel shape; kernel size; geometric model; geometric approximation

Barley serves primarily as a major animal feed crop; smaller amounts of barley are used in the malting processes and in health foods. Some researchers think about pressed barley grass as a potential source of some nutritional substances (e.g. vitamin C, polyphenols, phenolic compounds, proteins, amino acids, and saccharides) (Paulíčková *et al.* 2007). On the other hand, the prolamin protein fraction of barley can cause some adverse effects when ingested by people with the coeliac disease (Hulín *et al.* 2008).

Geometric features of cereal grains, including barley, are very important in the design of food engineering processes, such as the air transport, drying, milling and malting. In particular, kernel size and uniformity are important determinants of the malting quality. Their size and shape influence the electrostatic separation of barley kernels from

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extraneous material, as well as the development of sizing and grading machinery. Kernel shape is also significant for analytical prediction of its drying behaviour (Altuntas & Yildiz 2007; Isik & Unal 2007).

The weight per thousand kernels is a typical process indicator of the mean kernel size.

In addition to the weight test, another criterion for malting barley is that at least 85% of the malting barley grain (free of extraneous matter) should be retained on a 2.5 mm sieve (Fettell *et al.* 1999). In fact, the Czech standards (ČSN 46 1100-5) recommend the test weight of 90% for malting barley.

The coefficients of variation for the kernel size parameters are usually low. For example, Shouche *et al.* (2001) measured the geometric characteristics of Indian wheat varieties and obtained the variation coefficients in the range of 2–3% for all varieties. Tanska *et al.* (2005), testing the use of digital image analysis for the estimation of rapeseed quality, determined the variation coefficients of 2–7% for the basic geometric parameters. And Firatligil-Durmuş *et al.* (2008), investigating lentil size, obtained coefficients of variation in the range of 3.4–5.3%.

Grain density is another important factor that influences the design and control of many food engineering processes. Hampl (1970) stated the average densities for cvs White Hulles and Coast (six-row) as 1330 kg/m^3 and 1130 kg/m^3, respectively, while Güner (2007) has characterised recently barley as having the kernel density of 995 ± 7 kg/m^3.

Owing to the inconsistencies and variations in the shapes, surface profiles, and dimensions of barley kernels, it is very difficult to evaluate the actual surface areas and volumes.

Čvančara (1967) reported 1.31 m^2/kg as the specific area of wheat. Firatligil-Durmuş *et al.* (2008) used image analysis to measure the specific surface area of lentils, reporting 0.594 m^2/kg for red lentils and 0.579 m^2/kg for green lentils. But, to the best of our knowledge, no specific surface area data has been published for barley recently.

The shapes of most natural food materials generally resemble standard geometric objects, this feature being utilised in the theoretical estimation of their surface areas. As the use of a digital calliper for making manual measurements of the size is prone to human error, it is not the most effective way of estimating the dimensions and, subsequently, the volumes of grains. Nowadays, image analysis methods are most commonly used to make such measurements. Computer vision is one of such non-destructive methods that involve image analyses and image processing operations (Koc 2007).

The majority of computer vision applications used in the food industry focus on the food quality and grading (Fernandez *et al.* 2005; Yang *et al.* 2005; Blasco *et al.* 2007; Mendoza *et al.* 2007), the evaluation of mixing (Tukiendorf *et al.* 2003), crystallisation (Bubník *et al.* 2000), separation and aggregation processes (Šárka *et al.* 2006a, b), and the analysis of food texture and microstructure (Mezreb *et al.* 2003; Švec & Hrušková 2004; Soral-Smietana & Krupa 2005).

Numerous studies have recently been published on the possibility of using the computer vision in the estimation of grain quality. Such studies are aimed at determining the kernel geometry and colour for the purpose of identifying the species, varieties, and types of microbiological contamination, as well as the extent of mechanical and/or thermal damage (Tanska *et al.* 2005). Morishima *et al.* (1996), for example, measured the shape of rice using the image analysis. And Sakai *et al.* (1996) analysed the effects of polishing methods on the shape of various varieties of brown rice and polished rice. Yadav and Jindal (2007a, b) modelled the changes that occur in the dimensions of milled rice kernels during cooking and soaking.

In this study, we used six varieties of barley to test the potential for using digital image analysis to determine the characteristics of the kernel size. We also designed and used five geometric models for estimating the volume and surface area of barley kernels.

MATERIALS AND METHODS

Samples of barley

Six cultivars of *Hordeum vulgare* L. (two-rowed spring barley varieties) were obtained (Agricultural Research Institute Kroměříž, Ltd., Kroměříž, Czech Republic): Jersey (JE), Sebastian (SE), Malz (MA), Tolar (TO), KM 1910 (KM) and Merlin (ME). Cultivar Merlin is a hulles variety as well as the experimental variety KM 1910. KM 1910 was breaded by Agricultural Research Institute Kroměříž, Ltd.

Methodology of particle size measurement using the LUCIA system

Image analysis. Digital image analysis was performed on 600 individual barley kernels (100 kernels per cultivar). The images were acquired using a high resolution, low-noise Cohu 2252 CCD colour video camera equipped with object lenses with a magnification of 2.5 and 0.5 in sequence. Each image was analysed using the software LUCIA Ver. 3.52 and NIS – Elements Ver. 2.3 (Laboratory Imaging Co., Czech Republic). Prior to the analyses, calibration was performed using a special glass grid. For lighting, a lighting table was used.

Seven geometric parameters were measured: projected area, equivalent diameter, perimeter, MinFeret, MaxFeret, circularity, and elongation. To create 3D geometric models, the height and crease depth of each kernel were measured using a digital calliper (replicated five times).

Geometric approximation of volumes and surface areas of barley kernels. Five models were considered for barley kernels (Figures 1–5). With the exception of the general ellipsoid (Model 0), the volume and surface area calculations were performed iteratively using optimisation methods in Excel.

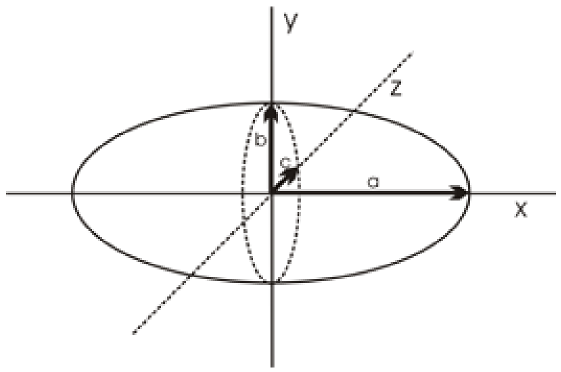

Figure 1. Model 0 – General ellipsoid

The following equations were used to realise the geometric simulation of the volume and surface area of the general ellipsoid (Model 0), with Maple 9.0 being subsequently used to calculate the surface area:

$$V = 4/3\ \pi abc \tag{1}$$

$$S = 2\pi c^2 + \frac{2\pi b}{\sqrt{(a^2 - c^2)}} \left[c^2 I(k,\phi) + (a^2 - c^2)\, J(k,\phi) \right] \tag{2}$$

where: a, b, c ($a > b > c$) represent the semi-axes of the general ellipsoid

$$I(k,\phi) = \int_0^{\phi} \frac{d\psi}{\sqrt{(1 - k^2 \sin^2\psi)}} \tag{3}$$

$$J(k,\phi) = \int_0^{\phi} \sqrt{(1 - k^2 \sin^2\psi)}\, d\psi \tag{4}$$

$$\phi = \arccos b/a \tag{5}$$

$$k = \frac{a}{b}\sqrt{\frac{b^2 - c^2}{a^2 - c^2}} \tag{6}$$

The following three models (Models 1–3) represent various combinations of two parts of a general ellipsoid with one or two cone frustums (calculated as the difference between two cones). Model 4 was a combination of two cone frustums.

The volume and surface area of part of a general ellipsoid were calculated as:

$$V = \pi\, b\, c \int_0^e \left(1 - \frac{x^2}{a^2}\right) dx = \pi\, b\, c\, e\left(1 - \frac{e^2}{3a^2}\right) \tag{7}$$

$$S = \frac{\pi}{2}\left(b + c + \sqrt{2(b^2 + c^2)}\right)\frac{1}{a}\left(\frac{1}{2}e\sqrt{a^2 - e^2} + \frac{e^2}{2}\arcsin\frac{e}{a}\right) \tag{8}$$

where:

e – x-coordinate for the point at which a general ellipsoid passes a cone (mm) (Figure 2)

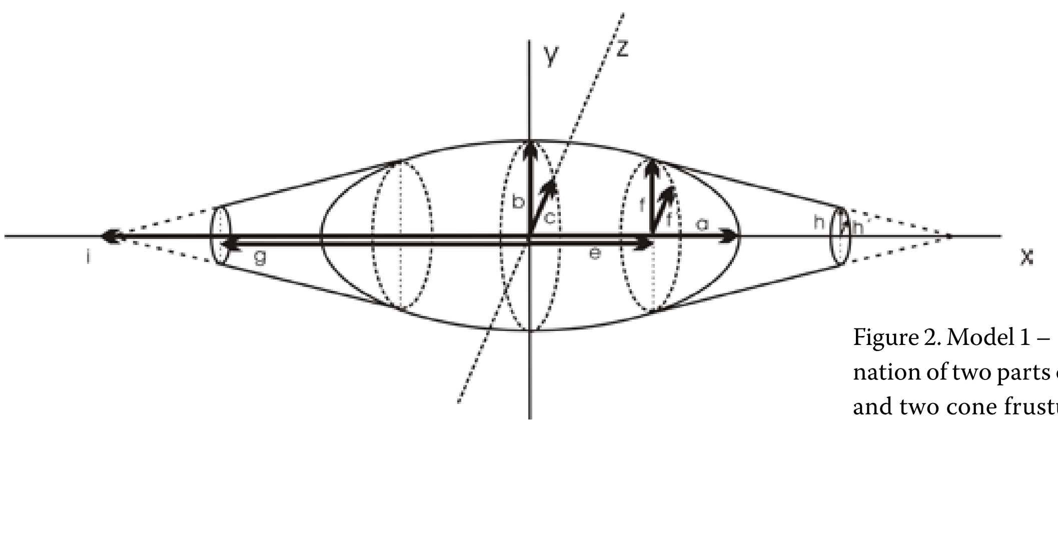

Figure 2. Model 1 – Symmetric combination of two parts of general ellipsoid and two cone frustums

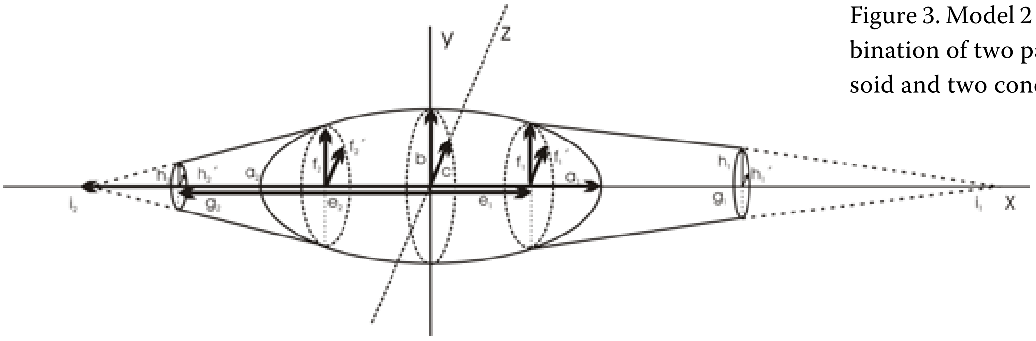

Figure 3. Model 2 – Asymmetric combination of two parts of general ellipsoid and two cone frustums

The volume and surface area of a general cone was calculated as:

$$V = \frac{\pi f f' H}{3} \quad (9)$$

where:

H ($H = g - e$) – height of the cone

f, f' – semi-axes of an ellipse in the cone base (Figure 2)

$$S = \pi \sqrt{f f'} p \quad (10)$$

where: $$p = \frac{(\sqrt{H^2 + f^2} + \sqrt{H^2 + f'^2})}{2} \quad (11)$$

The surface area of the cone base was calculated:

$$S = \pi \times h \times h' \quad (10)$$

where:

h, h' – semi-axes of an ellipse in the cone base (Figure 2)

Measurements of volumes and projected areas of barley kernels. The comparison of the volumes obtained from the geometric approximations with those measured by the pycnometric method was described by Firatligil-Durmuş *et al.* (2008). The projected area values measured by image analysis were compared with those calculated for the two-dimensional shapes.

RESULTS AND DISCUSSION

Geometric parameters of barley

The length, width and height ranges obtained for the barley kernels are shown in Table 1. The maximum range of the kernel length was measured using the cultivar Tolar and it was greater than those recorded by Güner (2007).

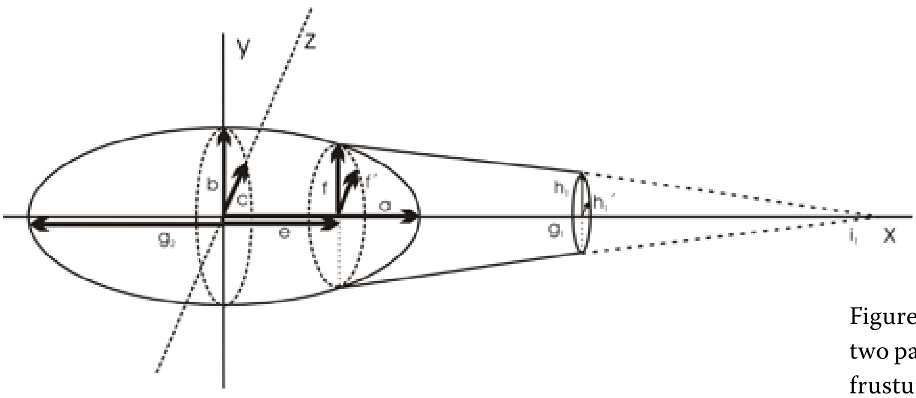

Figure 4. Model 3 – Combination of two parts of general ellipsoid and cone frustum

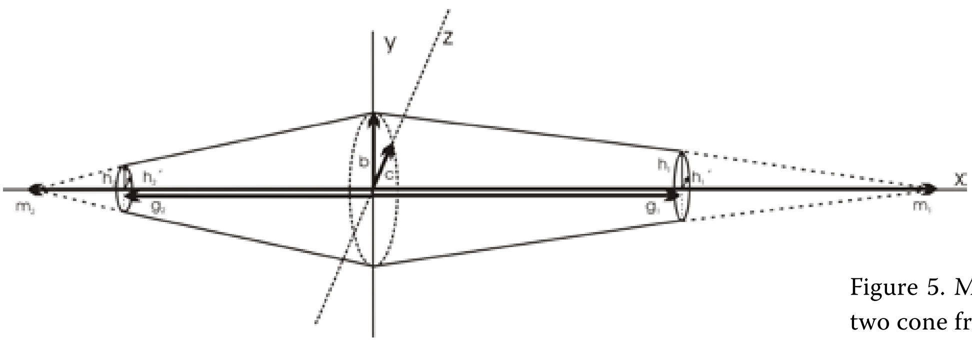

Figure 5. Model 4 – Combination of two cone frustums

Table 1. Minimum and maximum sizes of barley kernels for the selected cultivars

Cultivar	Lenght (mm)	Width (mm)	Height (mm)
JE	7.12–9.49	2.62–4.13	2.06–3.11
SE	7.49–9.48	3.47–4.26	2.46–3.17
MA	7.06–10.32	3.08–4.19	2.45–3.31
TO	8.33–13.23	3.74–4.73	2.00–3.68
KM	6.39–10.69	2.71–4.31	1.57–2.86
ME	7.07–10.07	2.94–4.14	1.93–3.17

For each of the nine size parameters measured (seven by image analysis; two by digital calliper), Table 2 presents the mean, standard deviation, and coefficient of variation values obtained from 100 samples of each barley cultivar. The differences between our results and those reported by Nielsen (2003) are very small. The coefficient of variation is between 4–12% for most of the basic geometric parameters, the exception being the range of 28–47% obtained for the crease depth. Our variation coefficients are higher than those reported by Shouche *et al.* (2001) for Indian wheat varieties, Tanska *et al.* (2005) for rapeseed and Firatligil-Durmuş *et al.* (2008) for lentils.

The average projected areas measured for one kernel were smaller than the 25.10 mm^2 reported

Table 2. Geometric parameters of barley seeds

Geometric parameter		JE	SE	MA	TO	KM	ME
	mean value	20.78	23.40	22.16	30.63	23.39	23.37
A (mm^2)	*CV*	10.29	8.38	10.82	10.51	12.11	10.27
	SD	2.14	1.96	2.40	3.22	2.83	2.40
	mean value	5.14	5.45	5.30	6.24	5.45	5.45
d_e (mm)	*CV*	5.23	4.24	5.42	5.32	6.15	5.22
	SD	0.27	0.23	0.29	0.33	0.34	0.28
	mean value	20.45	20.93	20.68	24.22	20.61	20.35
Perimeter (mm)	*CV*	5.72	9.40	7.15	6.50	6.80	5.85
	SD	1.17	1.97	1.48	1.57	1.40	1.19
	mean value	8.50	8.66	8.50	10.12	8.76	8.57
MaxFeret (mm)	*CV*	5.63	4.99	7.27	7.92	8.14	6.62
	SD	0.48	0.43	0.62	0.80	0.71	0.57
	mean value	3.47	3.90	3.69	4.24	3.67	3.72
MinFeret (mm)	*CV*	6.88	4.57	5.54	5.57	8.66	6.33
	SD	0.24	0.18	0.20	0.24	0.32	0.24
	mean value	2.63	2.85	2.85	2.79	2.37	2.45
Height (mm)	*CV*	7.50	5.14	6.12	8.19	9.10	8.44
	SD	0.20	0.15	0.17	0.20	0.22	0.21
	mean value	0.25	0.23	0.24	0.39	0.32	0.30
h_r (mm)	CV	35.87	45.50	32.93	28.55	32.99	46.62
	SD	0.09	0.10	0.08	0.11	0.10	0.14

Table 3. Projected areas obtained for 100 kernels of each barley cultivar by all geometric models

	JE	SE	MA	TO	KM	ME
IA	20.78	23.40	22.16	30.59	23.42	23.37
M0	23.20	26.53	24.67	33.73	25.32	25.07
Δ %	*10.46*	*11.79*	*10.20*	*9.31*	*7.50*	*6.78*
M1	22.08	23.52	23.03	30.48	23.40	23.35
Δ %	*5.88*	*0.51*	*3.77*	*0.36*	*0.09*	*0.08*
M2	21.87	23.43	22.85	30.69	23.49	23.34
Δ %	5.00	–0.13	*3.04*	*–0.33*	*–0.30*	*0.13*
M3	21.92	23.59	23.11	31.01	23.44	23.43
Δ %	*5.22*	*0.79*	*4.11*	*–1.37*	*–0.09*	*–0.26*
M4	21.56	22.26	22.43	28.76	21.72	21.05
Δ %	*3.63*	*–5.01*	*1.21*	*5.98*	*7.26*	*9.92*

M0–4 – models 0–4, PM – pycnometric measurement, IA – measured by image analysis

by Güner (2007) for all cultivars except the Tolar cultivar whose value of the average projected area was 30.63 mm^2.

Comparison of geometric model approximations with projected areas and volumes measured by pycnometric method

For each of the barley cultivars analysed and five models used, Table 3 presents the projected areas calculated from the two dimensions measured (MaxFeret, MinFeret).

For each cultivar, the greatest difference between the projected area value measured by image analysis and that calculated from the geometric models was obtained for Model 0. The other models (1–4) provided a good projected area approximation for all cultivars.

From the three dimensions measured, the volumes of the barley kernels were estimated. Table 4 compares the volumes determined using geomet-

Table 4. Comparison of volumes obtained for 100 kernels of each barley cultivar by pycnometric measurement and geometric approximation

	JE	SE	MA	TO	KM	ME
PM	3.00	3.60	3.77	3.71	2.64	2.62
M0	4.09	5.05	4.70	6.29	4.01	4.12
Δ %	*26.48*	*28.78*	*19.79*	*41.35*	*34.24*	*36.86*
M1	3.59	4.03	4.00	5.16	3.43	3.60
Δ %	*16.36*	*10.71*	*5.90*	*28.44*	*23.72*	*27.73*
M2	3.55	3.99	3.97	5.22	3.47	3.60
Δ %	*15.36*	*9.88*	*5.08*	*29.34*	*24.60*	*27.77*
M3	3.64	3.99	4.13	5.28	3.47	3.65
Δ %	17.42	9.84	8.77	30.10	*24.71*	*28.83*
M4	3.43	3.59	3.81	4.58	2.96	2.93
Δ %	*12.48*	*–0.28*	*1.00*	*19.51*	*11.76*	*11.25*

M0–4 – models 0–4, PM – pycnometric measurement, IA – measured by image analysis

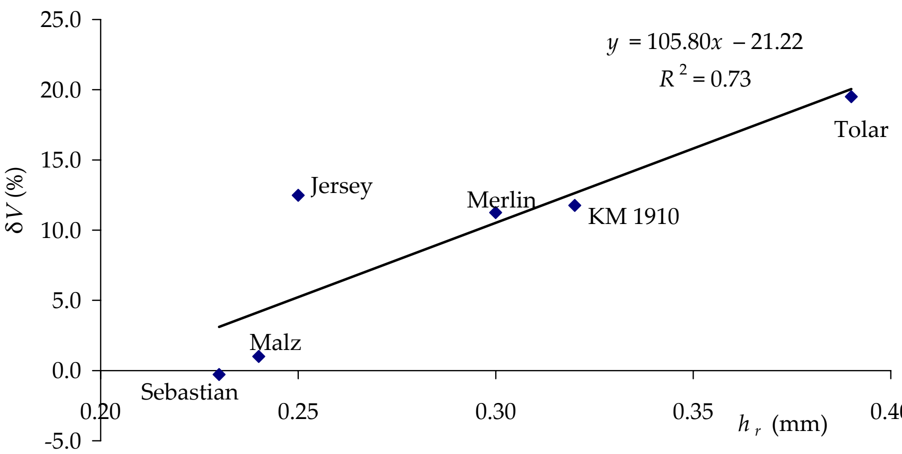

Figure 6. Dependence of the relative volume difference on the crease depth

ric approximation with those measured by the pycnometric method; the percentage differences obtained between the volumes estimated using these two methods. Model 4 provided the best values of the volume, the differences were in the range of −0.28–19.51%.

It is evident that the volume difference is closely related to the crease depth. The apparently low correlation ($R > 0.8$) (Figure 6) has been caused by the measurement accuracy and the geometry of the crease. In summary, when we subtract the linear correction from the equation in the graph, the average difference between the image processing method and the traditional methods is decreased max. 7.3% in all cases. This demonstrates that the image processing implementation yielded the results which largely agree with the traditional measurements. This approximation provided the best fit and is thus consequently better than that reported by Gaston *et al.* (2002) (11.31% for percentage difference between the volumes of Argentina wheat cultivar estimated by the ellipsoidal approach and the pycnometric method).

Relationships of surface area and weight of 1000 kernels

Prediction equations for the surface areas of foodstuffs (apple and meat) were reported by Goni *et al.* (2007). The values of R^2 of the relation between the weight of one piece of food and the surface area were 0.93, 0.98, and 0.95, respectively, for granny smith apple, red delicious apple and meat piece. Eifert *et al.* (2006) reported a linear equation to predict the surface areas of apples, cantaloupe, strawberry, and tomato from the weight measurements with R^2 equal to 0.47, 0.75, 0.96, and 0.87, respectively.

That is why the estimated values of the surface area of 1000 kernels were correlated with the weight

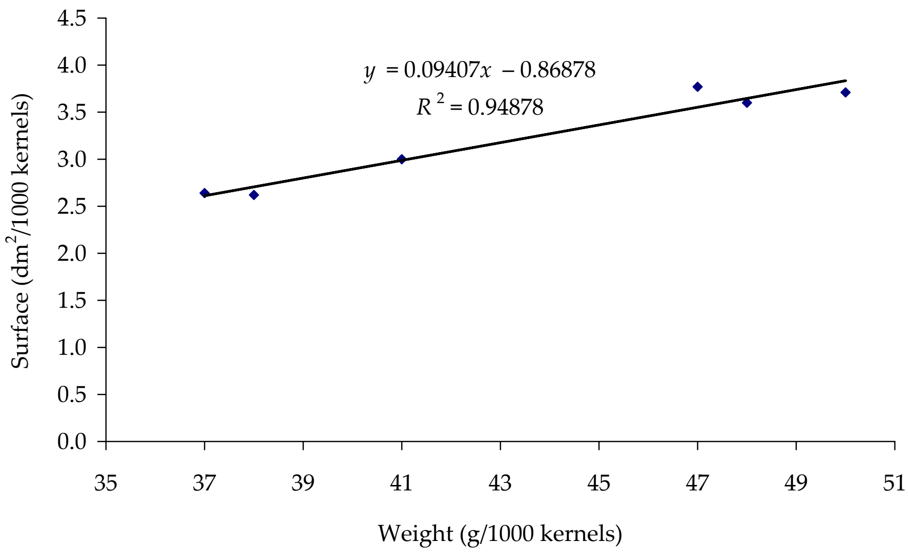

Figure 7. Dependence of the surface area on the weight of 1000 kernels of barley cultivars

Table 5. Main characteristics of barley grains

Characteristic	JE	SE	MA	TO	KM	ME
Weight per 1000 kernels (g)	41	48	47	50	37	38
Grain density (kg/m^3)	1355.7	1327.8	1251.2	1367.0	1433.8	1470.1
Specific volume (dm^3/kg)	0.737	0.753	0.799	0.910	0.790	0.767
Specific surface area (m^2/kg)	1.56	1.35	1.43	1.57	1.59	1.52
Surface area per 1000 kernels (dm^2)	6.37	6.44	6.73	7.38	5.87	5.76

of 1000 kernels. The fitting correlation of the calculated surface area to the weight of 1000 kernels is shown in Figure 7 for the cultivars measured.

This simplification enables to estimate the specific surface without the manual measurement of the height. The weight of 1000 kernels is thus fully sufficient for this purpose.

Main characteristics of barley grains

The main characteristics of the barley samples investigated are given in Table 5. Model 4 was used for the volume and surface area computations, which were performed iteratively using the optimisation methods in Excel.

The specific surface area calculated is higher than reported by Čvančara (1967) for barley grains. Additionally, the value of 9.5 dm^2 reported by Čvančara (1967) for the surface area per thousand kernels of barley is very incorrect. Our results are comparable with those of AL-Mahasneh & Rababah (2007), who obtained a surface area of 6.10 dm^2 for green wheat grains with a moisture content of 41.5%.

With regard to the sample weight, the results reported by Güner (2007) are higher than those for Jersey, Sebastian, Malz, and Tolar cultivars and are comparable with KM 1910 and Merlin cultivars, which have smaller weights (37–38 g per 1000 kernels) than the other cultivars.

The grain densities measured for our cultivars were higher than those given by Güner (2007), but comparable with the values reported for cv. White Hulle by Hampl (1970).

CONCLUSION

We investigated and determined the size variations between the kernels of six barley cultivars grown in the Czech Republic. To determine the geometric parameters of the kernels of each cultivar, we used an image analysis system, which involved developing a suitable measurement methodology, selecting the optimal magnification level, setting-up lighting, and creating a subroutine including the contrast and threshold values.

Five geometric models were developed and used to estimate the volume and surface area of each type of kernel. The geometric model consisting of two cone frustums (Model 4) provided the best approximation of the volume with all cultivars (percentage differences ranging from –0.28–19.51%). The results from Model 4 were corrected taking into consideration the measured average crease depth. Compared with the traditional measurement of the volume, the percentage difference of the geometric approximation method was less than 7.3%. The same model was used to obtain the values of specific surface area ranging from 1.35–1.59 m^2/kg.

In order to generalise the results obtained with the measured samples of barley, the estimated values of the surface area were also correlated with the weight of 1000 kernel and a good correlation was obtained. Therefore, the determined weight of 1000 kernels can help to estimate very quickly the specific area of barley for engineering calculations.

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Symbols and units

a, b, c	semi-axes of the general ellipsoid (mm)
A	scanned cross-section (projected area) of the kernel (mm^2)
CV	coefficient of variation (%)

d_e	equivalent diameter of the kernel (mm), defined $d_e = \sqrt{4A/\pi}$
e	x-coordinate for the point at which a general ellipsoid passes a cone (mm) (Figure 2)
f, f', h, h'	semi-axes of ellipses in cross-section (mm) (Figure 2)
g	x-coordinate for the end point of the kernel (mm)
H	height of the cone (mm)
h_R	crease depth of the kernel (mm)
i, m	x-coordinate for the end point of the cone (mm) (Figure 2)
S	surface area of one kernel (mm^2)
SD	standard deviation
V	volume of one kernel (mm^3)
x, y, z	coordinates

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