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Analysis of the hair coat of domestic cats with special focus on histological structure

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The aim of the study was to characterize the hair coat of domestic cats. The research material consisted of hairs of different fractions collected in winter from female cats with a uniform hair coat colour: white, cream, red, brown and black. The hairs were divided into individual fractions, i.e. underhair, bristle hair and guard hair, and the following characteristics were evaluated: thickness, length, long and short axis length, stress at break and elongation. SEM (scanning electron microscope) images of all types of hair were taken and used to characterize each hair type and to calculate the number of scales per mm of hair length. The content of ions of various chemical elements was determined as well. Underhairs, which accounted for the largest percentage in the coat, were the thinnest and shortest, and had the most regular and distinct scale pattern. Guard hairs were the least numerous, but were the longest and thickest of all hairs examined. Both guard and bristle hairs had irregular scales with jagged edges. The cross-sections of these hairs revealed the presence of all the layers, i.e. the cuticle, cortex and medulla. In the underhair fraction the medulla was observed only in red cats. In all hairs the share of carbon, oxygen and sulphur ions was largest; these are the main components of hair protein, i.e. keratin.

KEY WORDS: domestic cat, hair coat, histological structure

The hair coat is a characteristic feature of all mammals. It ensures protection against harmful environmental factors and heat insulation. It can also give the animal an attractive appearance. Due to its durability, mammal hair is a valuable research material providing information on the health status of the animal [1]. It can also be used as an indicator in assessing contamination of the environment inhabited by the animal [2, 7, 13].

The hair coat of the domestic cat is composed of overhair (guard and bristle hair) and underhair, whose quantity, as in other mammals, increases in winter [5]. In addition, hairs called vibrissae (whiskers) are present around the lips, nose, eyes and the pads of the paws. The colour of the hair coat colour is primarily determined by the overhair.

Three layers can be distinguished in the cross-section of the hair: the outermost cuticle, the middle cortex and an inner medulla, which is not present in most of the underhairs.

Physical characteristics of the hair, such as length, thickness, elongation, and stress at break, may be indicative of a proper or poor diet or of disease, but can also determine the potential use of the hair in the textile industry. Most research has thus far focused on the hair of livestock or wild animals [4, 6, 8, 9, 12], while only a few studies have described the hair coat of companion animals [2, 4, 10, 11], taking into account the physical characteristics of different types of hair or their histological structure.

Therefore the aim of this study was to analyse the hair coat of domestic cats of different colours in terms of physical parameters such as hair length, long and short axis length, diameter, elongation and stress at break. Additionally, the cuticle scales were described and the content of ions of various elements on the hair surface was analysed. The results of this study constitute a contribution to knowledge of the biology of cats.

Material and methods

The study was performed on the winter hair coat of domestic cats belonging to private pet owners. Their diet was based on commercially available feed and raw meat. The hair coat samples were collected from cats with a uniform coat colour: red, cream, white or brown. The samples were taken in February from females aged 3-4 years, from the left side of the body, about 5 cm from the spine at the height of the last rib. Each group of cats with different hair coat colour consisted of 6 animals.

To calculate the percentage share of each fraction, i.e. overhairs (bristle and guard) and underhairs, 1,000 hairs were randomly selected from each sample. The criterion for dividing hairs into fractions was their thickness, length and appearance. The hairs were separated into fractions and their length was measured using a projection microscope (MC-3) at a magnification of 500 x. Then the percentage share of each fraction was calculated.

The following parameters were determined in all fractions: hair length (mm), thickness (µm), stress at break (kg/mm^2) and elongation (%). The breaking force needed to calculate the stress at break and the elongation of the hair were measured using an electronic tensile testing machine (MATEST, Poland). The stress at break (kg/mm^2), which is a measure of strength, was calculated according to the formula $N=(P\text{x}10^4)/(\pi\text{x}d2\text{x}9.81)$, where N is the stress at break, P the breaking force (cN), and d the diameter of the hair cross-section (µm). The measurements were performed in the Skin and Hair Evaluation Laboratory of the Institute of Animal Breeding, Wrocław University of Environmental and Life Sciences.

SEM images of the hairs of individual fractions, showing the arrangement of cuticle scales and a cross-section of each type of hair, were made with a Zeiss 435 VP scanning electron microscope. A key for identification of mammalian hair was used to characterize the hair structure [12].

After the hairs had been divided into fractions, they were cleaned with ether and alcohol and rinsed in an ultrasound bath for about 5 minutes. Then the hairs were glued onto special tables and dusted with gold. The histological images were used to measure the thickness and long and short axis length of the hairs and the number of scales per mm of hair length. The cuticle of hairs of each colour was characterized as well. The percentage of various chemical elements was determined by X-ray microanalysis using a scanning electron microscope. The content of carbon, oxygen, sulphur, calcium, aluminium, magnesium, silicon, sodium, copper and phosphorus was determined. The content of elements was determined and the SEM images were made in the Electron Microscopy Laboratory of the Wrocław University of Environmental and Life Sciences.

Statistical analysis of the results was performed using Statistica 6.0. Mean values and standard deviations were calculated. Statistical significance of differences between means for groups was determined by one-way analysis of variance using Tukey's test.

Results and discussion

Table 1 shows the means and standard deviations of the following characteristics: percentage share of each hair fraction, thickness, length, long and short axis length, and the number of scales per mm of hair length.

The share of individual fractions, i.e. underhairs and overhairs (bristle and guard), was varied. In all cases the underhair accounted for the highest share, at 79.2-83.6%. The percentage of bristle hairs ranged from 8.8% to 16.0% and that of guard hairs from 4.2% to 9.6%.

Underhairs, which had the highest percentage share, were found to be the thinnest. Their thickness ranged from 10.6 (white) to 19.1 µm (red). The thickness of the bristle hairs ranged from 29.0 µm for brown hair to 41.8 µm for white hair. The thinnest guard hairs were observed in brown cats (45.0 µm) and the thickest in white cats (66.1 µm).

The shortest of the hair types were the underhairs, whose length varied from 0.81 to 1.76 cm, followed by the bristle hairs, from 1.25 to 2.31 cm, while the guard hairs were the longest, from 2.16 to 3.68 cm. The red cats had the shortest underhairs, bristle hairs and guard hairs, while the longest bristle hairs were noted in the black coats. The longest guard hairs were observed in the brown coats.

The length of the short axis ranged from 13.0 to 29.6 µm in the underhairs, from 19.0 to 41.3 µm in the bristle hairs, and from 24.9 to 65.0 µm in the guard hairs. The length of the long axis varied from 14.3 to 51.7 µm of the underhairs, from 28.3 to 66.3 µm for the bristle hairs, and from 51.0 to 79.3 µm for the guard hairs.

The number of scales per mm of hair was varied, ranging from 50 to 500. The red bristle hairs had the most scales and the underhairs of the same colour had the fewest.

Table 1

Means and standard deviations of the percentage share (%), thickness (µm), length (cm), short (µm) and long axis length (µm) and number of scales per mm of each type of hair

Hair colour	Type of hair		
	underhair	bristle	guard
1	**2**	**3**	**4**
	Percentage share of hair type		
Cream	83.2 ±6.4	12.6 ±1.7	4.2^{A} ±0.8
White	79.2 ±6.0	16.0^{ab} ±2.2	4.8^{B} ±1.0
Brown	81.6 ±5.6	8.8^{a} ±1.9	9.6^{AB} ±1.2
Black	83.6 ±6.9	9.2^{b} ±1.4	7.2 ±1.1
Red	82.7 ±6.7	12.2 ±1.1	5.1 ±0.7
	Thickness of hair type		
Cream	17.1^{A} ±2.6	32.7 ±7.5	51.8 ±7.6
White	10.6^{ABab} ±3.6	41.8^{A} ±6.7	66.1^{a} ±8.7
Brown	16.8 ±2.8	29.0^{AB} ±5.7	45.0^{abc} ±7.0
Black	18.7^{aB} ±2.6	39.0^{B} ±6.8	57.3^{b} ±3.9
Red	19.1^{b} ±2.1	35.5 ± 7.5	57.7^{c} ±7.6
	Length of hair type		
Cream	1.34 ±0.28	1.87 ±0.20	2.59 ±0.20
White	1.12 ±0.18	1.67 ±0.14	2.55 ±0.24
Brown	1.60^{a} ±0.25	2.60^{A} ±0.17	3.68^{b} ±0.25
Black	1.76^{A} ±0.32	2.31^{a} ±0.16	3.53^{a} ±0.27
Red	0.81^{Aa} ±0.21	1.25^{Aa} ±0.19	2.16^{ab}±0.28
	Short axis length		
Cream	18.3 ±1.1	30.3 ±2.6	43.3^{A} ±1.3
White	16.6 ±1.0	24.6 ±1.0	24.9^{BCD} ±1.6
Brown	17.3 ±0.7	19.0^{ab} ±1.0	48.6^{B} ±1.8
Black	29.6^{a} ±1.0	41.3^{a} ±2.5	65.0^{C} ± 3.0
Red	13.0^{a} ±0.9	36.6^{b} ±2.3	49.3^{D} ±2.0

1	2	3	4
	Long axis length		
Cream	51.7^{a} ±2.4	36.6 ±2.3	65.0 ±3.2
White	25.0 ±1.5	36.7 ±1.4	76.6^{a} ±3.0
Brown	40.0 ±1.9	28.3^{A} ±1.1	74.0 ±3.0
Black	51.7^{b} ±2.4	66.3^{A} ±1.7	79.3^{b} ±3.9
Red	14.3^{a,b} ±1.1	53.0 ±2.6	51.0^{a,b} ±1.9
	Number of scales per mm of hair		
Cream	140^{B} ±20	150^{a} ±11	200 ±12
White	200^{A} ±18	200 ±18	150^{A} ±16
Brown	150^{C} ±23	150^{b} ±16	200 ±13
Black	150^{D} ±19	150^{c} ±16	150^{B} ±13
Red	50^{ABCD} ±13	500^{abc} ±21	350^{AB} ±13

A, B, C, D – means within columns with the same superscripts differ significantly at $p<0.01$
a, b, c – means within columns with the same superscripts differ significantly at $p<0.05$

Table 2 presents the results for the strength and elongation of hairs depending on their colour and type.

Analysis of the stress at break of bristle and guard hairs revealed the greatest strength for the red bristle hairs and the lowest for the cream-coloured guard hairs. The percentage difference between the hairs of the greatest and lowest strength was 59.43%. It should be emphasized that irrespective of colour the bristle hairs were stronger the guard hairs.

The greatest elongation was observed in brown guard hairs (32.1%) and the lowest in black guard hairs (9.8%). A similar tendency was observed for bristle hairs.

The content of chemical elements on the surface of each of the hair types is shown in Table 3. Carbon had the largest share in the underhairs of all colours, with content in a range of 49.52-65.38%, followed by oxygen, from 24.61-42.29%, and sulphur, whose content ranged from 5.02 to 7.87%. Other elements were present in much smaller amounts, not exceeding 1%. The presence of sodium, aluminium and silicon was not noted in black cats, phosphorus was not observed in brown cats, and aluminium, magnesium and silicon were absent in the hair of cream-coloured cats. The greatest variation in the content of chemical elements was observed in the underhair of white and red cats, and the least variation in black cats. In the bristle hairs, as in the case of underhairs, carbon had the largest percentage (45.72-72.33%), followed by oxygen (20.42-43.93%) and sulphur

Table 2
Means and standard deviations of stress at break (kg/mm^2) and elongation (%) for each hair type

Hair colour	Type of hair	
	bristle	guard
	Stress at break	
Cream	4.59^{A} ±1.13	3.00^{a} ±1.02
White	4.64^{B} ±1.37	3.28 ±1.40
Brown	5.83 ±1.45	3.15^{b} ±1.38
Black	6.78 ±1.41	4.31^{ab} ±1.45
Red	7.39^{AB} ±1.30	4.13 ±1.09
	Elongation	
Cream	14.35 ±1.46	15.40 ±1.68
White	22.70 ±1.76	23.15^{a} ±1.56
Brown	30.60^{AB} ±2.91	32.10^{A} ±1.90
Black	10.10^{A} ±1.21	9.80^{Aa} ±1.79
Red	10.75^{B} ±1.59	13.80 ±1.25

A, B – means within columns with the same superscripts differ significantly at $p<0.01$
a, b – means within columns with the same superscripts differ significantly at $p<0.05$

(6.37-8.03%). Here too the content of the remaining elements was about 1%. The share of carbon was also greatest in the guard hairs, in a range of 44.07-60.71%, while oxygen content ranged from 22.25% to 46.72% and sulphur from 5.68% to 7.03%. Other elements were detected in much smaller amounts, about 1%; only the sodium content in the guard hairs of brown cats attained a level of about 2%.

Figures 1-5 show the arrangement of cuticle scales and cross-sections of underhairs, bristle hairs and guard hairs of cats with different coat colours.

The underhairs of the cats with cream, brown, white and black colouration were characterized by a transverse arrangement of the scales with respect to the length of the hair, while the scales were arranged lengthwise only in red cats. The scales were not arranged in a ring pattern in any of the hairs, and the distances between them were large. Except for the hairs of red cats, whose scales were shaped like elongated petals, the scales had varying shapes and were arranged in irregular waves. The hair scales of cream-coloured cats had slightly jagged edges, while the others had smooth edges. The presence of a medulla,

Table 3
Content (%) of ions of chemical elements in each hair type

Element	Type of hair	Hair colour				
		cream	white	brown	black	red
Carbon	I	49.52^{a} ±5.98	63.62 ±7.36	58.67 ±5.30	55.55 ±3.12	65.38^{a} ±6.28
	II	45.72^{Aa} ±6.31	60.87^{a} ±6.98	48.16 ±6.25	72.33^{A} ±3.38	58.21 ±7.12
	III	47.00 ±5.73	60.71^{A} ±2.14	45.63^{AB} ±5.38	53.85 ±3.46	70.01^{B} ±8.13
Oxygen	I	42.29^{ab} ±6.13	27.22^{b} ±7.30	34.40 ±3.93	37.23 ±4.98	24.61^{a} ±6.13
	II	43.93^{a} ±6.32	29.77 ±3.88	42.21^{b} ±5.83	20.42^{ab} ±6.03	33.34 ±4.93
	III	46.72^{a} ±5.88	32.25 ±3.20	44.51^{ab} ±6.12	38.54 ±4.11	22.25^{b} ±3.38
Sulphur	I	7.56^{a} ±1.10	7.19 ±0.59	5.02^{ab} ±0.92	7.22 ±0.63	7.87^{b} ±1.32
	II	7.09 ±1.31	8.03^{A} ±1.12	7.62 ±1.01	6.37^{AB} ±0.71	7.94^{B} ±1.20
	III	5.68 ±0.98	6.31 ±1.10	6.71 ±1.02	7.03 ±0.62	6.79 ±0.92
Sodium	I	0.60 ±0.040	0.22^{a} ±0.03	0.80^{ab} ±0.04	–	0.13^{b} ±0.03
	II	1.49^{a} ±0.083	0.27^{ab} ±0.02	0.83 ±0.04	0.25^{a} ±0.03	0.24^{b} ±0.08
	III	–	0.17^{a} ±0.01	2.09^{ab} ±0.09	–	0.13^{b} ±0.04
Aluminum	I	–	0.51 ±0.04	0.35 ±0.09	–	0.33 ±0.04
	II	0.47 ±0.03	0.51 ±0.04	0.28^{a} ±0.08	0.62^{a} ±0.07	–
	III	0.60 ±0.06	0.42 ±0.05	1.06^{a} ±0.08	0.13^{a} ±0.01	0.82 ±0.06
Magnesium	I	–	0.12 ±0.06	0.30 ±0.08	–	0.15 ±0.03
	II	0.55 ±0.06	–	0.20 ±0.07	–	–
	III	–	–	–	–	–
Calcium	I	0.03^{a} ±0.02	0.94^{a} ±0.09	–	–	0.35 ±0.05
	II	–	0.55 ±0.04	–	–	0.27 ±0.05
	III	–	0.13 ±0.01	–	–	–
Copper	I	–	0.18 ±0.01	–	–	–
	II	–	–	–	–	–
	III	–	–	–	–	–
Phosphorus	I	–	–	–	–	–
	II	–	–	0.71 ±0.08	–	–
	III	–	–	–	–	–
Silicon	I	–	–	0.45 ±0.07	–	1.19 ±0.10
	II	0.76 ±0.09	–	–	–	–
	III	–	–	–	0.45 ±0.028	–

I – underhair; II – bristle; III – guard
A, B – means within a row with the same superscripts differ significantly at $p<0.01$
a, b – means within a row with the same superscripts differ significantly at $p<0.05$

which filled almost the entire interior of the hair, was noted in the underhairs of white and red cats, while the remaining hairs were filled with a compact cortical layer. All hairs were oval in cross-section.

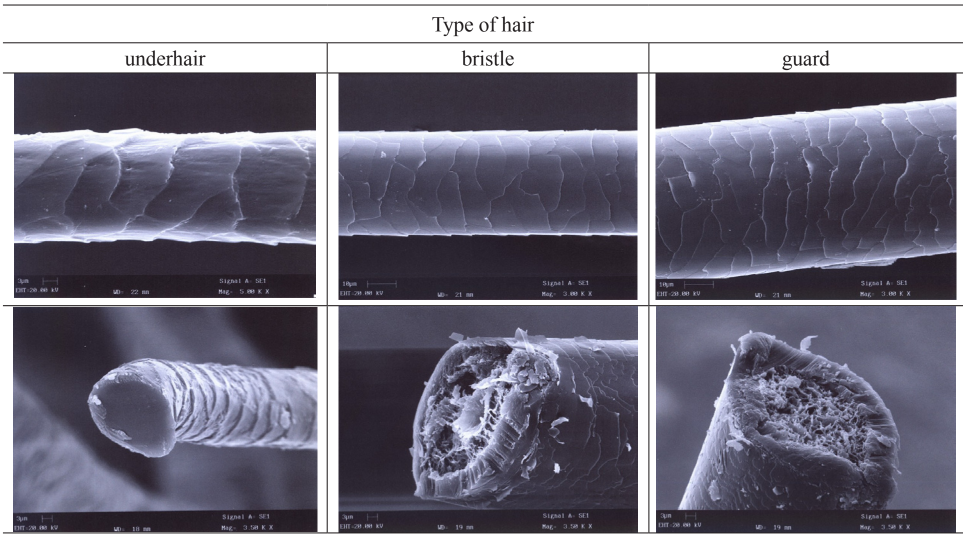

Fig. 1. Cuticle and cross-section of cream-coloured hair

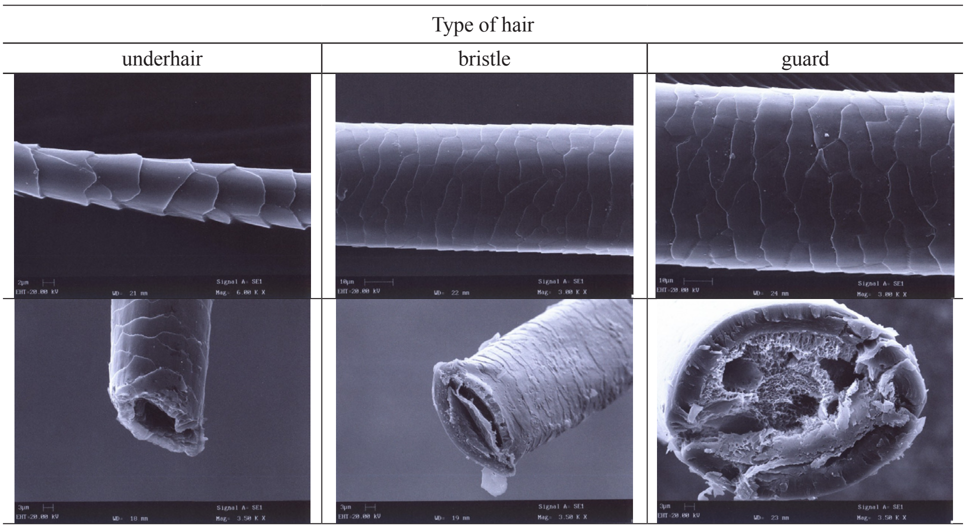

Fig. 2. Cuticle and cross-section of white hair

The cuticle scales of the bristle hairs of cream-coloured, white, brown and black cats were similarly arranged in a regular wave with smooth edges, except for the cream-coloured cats, in which the edges were slightly jagged. The cross-section of these

Type of hair		
underhair	bristle	guard

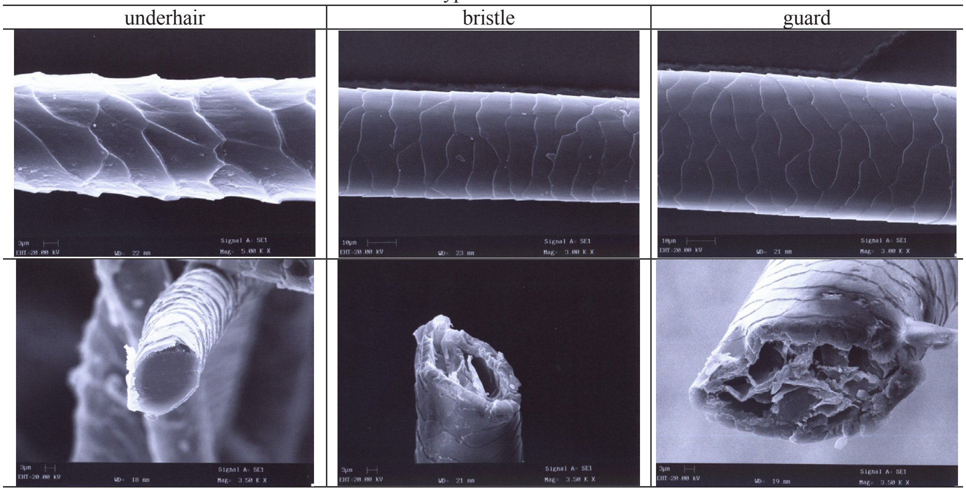

Fig. 3. Cuticle and cross-section of brown hair

Type of hair		
underhair	bristle	guard

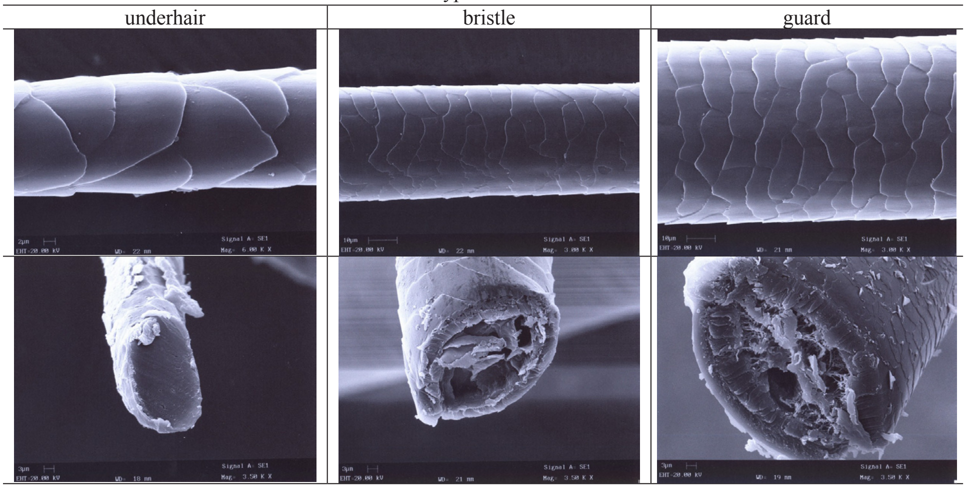

Fig. 4. Cuticle and cross-section of black hair

hairs was oval, and the interior was nearly completely filled by the medulla. The cuticle scales of the bristle hairs of red cats also had a regular arrangement. The distances between the scales were significantly smaller than in the other cats and their edges

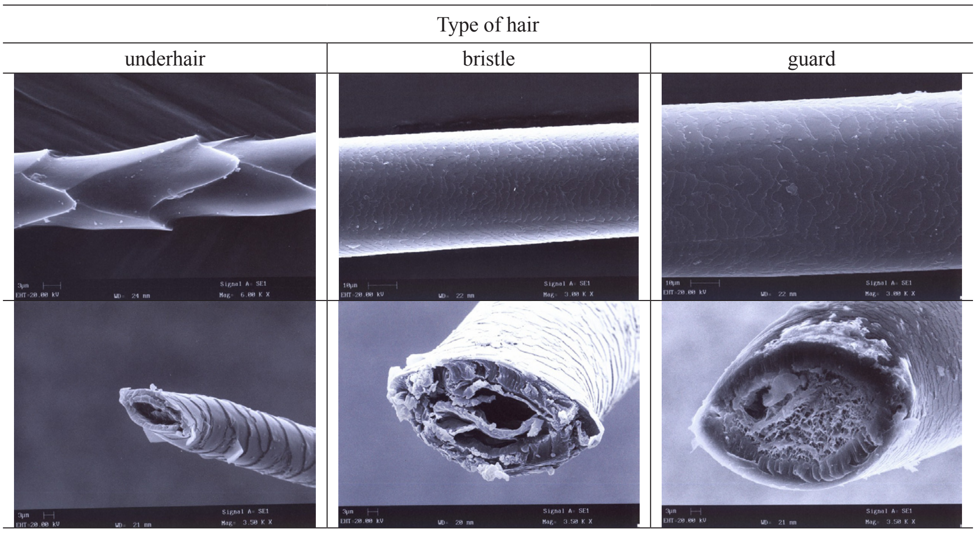

Fig. 5. Cuticle and cross-section of red hair

were very jagged. As in the other hairs, the interior was almost completely filled by the medulla.

The scales of the guard hairs of all examined cats were arranged in the form of a regular wave. As in the case of bristle hairs, they had smooth edges, except for the cream-coloured and red hairs. The scales were arranged transversely relative to the length of the hair. The distances between individual scales can be described as intermediate. In cream-coloured cats the scales were slightly jagged, while in red cats they had clearly jagged edges and were closer together than in the case of the other coat colours. The cross-section of all hairs was oval, and they were mostly filled with the medulla.

Due to the scarce literature concerning the hair coat of cats, it is difficult to discuss the results. The presence of three types of hairs, i.e. underhair, bristle and guard hair, was detected in all examined hair coat samples; underhairs were the most numerous and guard hairs the least. The study demonstrated that hairs of different colours differed in thickness. The different lengths of underhairs, bristle hairs and guard hairs confirmed the superposition of the components of the hair coat. The undermost, shortest layer was formed by the underhairs and the middle layer by the bristle hairs, while guard hairs were the longest and also the least numerous.

The strength of the guard hairs of the cats was found to be similar to the hair strength of fur-bearing animals [6, 9], while the strength of bristle hairs was greater. For comparison, the hairs of some breeds of dogs have a strength of about 15 kg/mm^2 [4], similar to that of sheep wool. Elongation of guard and bristle hairs was similar in the hair coats of cats of all colours.

The percentage analysis of the content of elements revealed the highest amounts of carbon, oxygen, and sulphur in the hairs, i.e. the elements forming keratin, the major hair protein [2, 11].

Histological structure, in addition to thickness and length, is a very important feature of hairs belonging to different species [3, 8, 12]. The scales of the outermost layer of the hairs analysed, i.e. the cuticle, was characterized by considerable diversity of shape, dimensions and number per mm of hair length. Regularly overlapping scales were observed, with clear contours, smooth edges, and an elongated shape, particularly in the case of underhairs. The scales observed in the bristle and guard hairs had an irregular structure and smooth wavy edges. Only the cuticle layer of red hairs differed in appearance from the others: the scales of underhairs were elongated, while those of the guard and bristle hairs were jagged. The interior of all hairs had a similar structure. The underhairs of white and red cats had a medulla layer, while in case of other colours they were filled with a dense cortex. All guard and bristle hairs contained a well-developed medulla. The differences in cuticle appearance and in the number of scales in the hairs of the red cats as compared to the other coat colours may result from the histological images having been taken at different sites. Teerink's [12] key to identification of mammalian hair showed that differences in the arrangement of scales may be noted along the length of the hair. In the domestic cat, the scales closer to the tip of the hair may be more jagged, smaller, and more numerous than on the part of the hair closer to the skin.

In conclusion, it should be emphasized that the study evaluated the hair coat of mixed-breed cats, in which no breeding work is carried out, and thus the results should be a valuable contribution to knowledge of the biology of mammalian hair coats.

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