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Size-age and histomorphological indicators of the Arctic grayling (*Thymallus arcticus*) of Putorana Nature Reserve

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In waterbodies of high latitudes, ichthyofauna of the boreal foothill complex is highly sensitive to unfavorable factors. Poorly studied and extremely vulnerable freshwater ecosystems of the Subarctic require an especially close attention, considering conditions of global climate changes and increasing anthropogenic impact. An important method of their protection is creation of Specially Protected Natural Areas (SPNA) with purpose of preserving natural ecosystems in their intact state. However, territories that are not subjects of anthropogenic influence are extremely rare presently. While studying the Arctic grayling (*Thymallus arcticus*) of the Irkinda River (the Putorana Plateau), flowing through the territory of Putorana Reserve, some histopathologies pointing on an unstable ecological situation in this region were revealed. The noted initial stages of pathological process in branchial apparatus, namely – hyperplasia, aneurysms, fusion of respiratory lamellae, and an increase of cells layers in intercalary epithelium – indicate suppression of respiratory function. The reproductive system is less affected, but abnormalities are also found in it. Resorption of vitellogenic oocytes was revealed in 83% of individuals. Moreover, all the males of the Arctic grayling took part in the past spawning, while the number of spawned females was not more than 67%.

Keywords: histological analysis, Arctic grayling, gonads, gills, Irkinda River, Putorana Plateau.

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Размерно-возрастные и гистоморфологические показатели сибирского хариуса (*Thymallus arcticus*) Путоранского заповедника

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В водоёмах высоких широт ихтиофауна бореального предгорного комплекса весьма чувствительна к неблагоприятным факторам. В условиях глобального изменения климата и возрастающего антропогенного воздействия малоизученные и крайне уязвимые пресноводные экосистемы Субарктики нуждаются в пристальном внимании. Важным видом охраны является создание особо охраняемых природных территорий с целью сохранения природных экосистем в нетронутом состоянии. Однако в настоящее время территории, не подверженные антропогенному влиянию, встречаются крайне редко. При исследовании сибирского хариуса (*Thymallus arcticus*) р. Иркинда (плато Путорана), протекающей по территории Путоранского заповедника, выявлены гистопатологии, указывающие на нестабильную экологическую ситуацию данного региона. Отмеченные начальные стадии патологического процесса в жаберном аппарате – гиперплазия, аневризмы, слияние респираторных ламелл и увеличение слоёв клеток вставочного эпителия – свидетельствуют об угнетении респираторной функции. Репродуктивная система менее поражена, но и в ней обнаружены отклонения. В яичниках у 83% особей отмечена резорбция вителлогенных ооцитов и, если в прошедшем нересте принимали участие все самцы сибирского хариуса, то доля отнерестившихся самок не превышала 67%.

Ключевые слова: гистологический анализ, сибирский хариус, гонады, жабры, река Иркинда, плато Путорана.

Environment stability determines normal functioning of vulnerable northern ecosystems. However, climate changes together with intensifying multi-factor anthropogenic pressure of recent decades are leading to degradation of the ecosystems, as well as decrease of biological diversity and number of species [1]. In this regard, along with inventory of the key nature communities in Arctic latitudes, it is necessary to determine their current morphological and functional status. In order to establish a full picture of the ongoing changes, their initial state should be identified – the "zero point" of the reference. Specially Protected Natural Areas (SPNA) are becoming the standard of certain natural zones, a reserve for subsequent dispersal of species in impact areas.

Due to native accumulation entity of natural reservoirs, aquatic organisms are the most important indicators of environment state. Fish represent the highest trophic level of freshwater ecosystems. In terms of the volume of fresh water, lakes of the Putorana Plateau rank second after Lake Baikal. They are characterized by a complexly formed hydro system and a unique variety of salmonid fish [2]. In northern waterbodies, salmonids are represented by arctic freshwater (salmon, whitefish) and boreal foothill (grayling) faunistic complexes are the most sensitive to ecological regime changes. As a result of a long life cycle, certain age-related changes occur in structure of their internal organs and tissues. In conditions of environmental pollution, various types of pathologies are being accumulated. For the accurate description of long-term dynamics of ichthyocenosis, a detailed histomorphological analysis makes it possible to assess the ontogenetic history of studied individuals [3–7], and identify the incipient degenerative changes in organs and tissues.

As we know, graylings are freshwater fish that inhabit small fast rivers and cold lakes of Europe, Asia, and North America. The Arctic grayling *Thymallus arcticus* is a highly polymorphic species. It forms a large number of subspecies and other forms of a lower systematic level in the basin of the Arctic Ocean, from Kara to Chukotka and North America [8–11]. However, there are no histological studies of internal organs and their possible pathomorphological changes in this species carried out in high-latitude waterbodies of Eastern Siberia.

The purpose of the present study was to characterize the size-age composition and describe histomorphological state of vital organs of the Arctic grayling in a mountain river of the Putorana plateau in conditions of minimal anthropogenic load.

Material and Methods of the Research

The Irkinda mountain river flows through the territory of Putorana State Nature Reserve located in the northwestern part of the Putorana Plateau. The length of the watercourse is 66 km, the catchment area is 990 km^2. The water temperature varied from 8.5 to 11.9 °C during the study period. Collection of the material was implemented upstream of one of the most beautiful waterfalls of the plateau – the 27-meter Kitabo-Oron (Big Irkindinsky waterfall).

The Arctic graylings were caught in August 2016. 33 individuals of different ages of both sexes were examined and 80 histological preparations were made to assess the size-age composition, gonads histomorphology, and branchial apparatus.

Age was detected by studying the fish scales. In implementation of the work, we were guided by standard ichthyological methods [12] and histological methods [13]. Clinical and pathological examination of the fish was carried out [14, 15]. The prepared parts of the organs were fixed in Brodsky's mixture. Histological sections of gills, ovaries, and testes were stained with Heidenhain's iron hematoxylin and Heidenhain's azan method, after that they were placed under a cover slip in BioMount medium.

Histological and cytological measurements were made using an AxioCam MRc5 video camera on an AxioImager A1 microscope at magnification 40 to 1000. Using licensed software AxioVision Release 4.7.1, resorbing oocytes and empty follicles were noted on ovarian cuts, diameter of oocytes and their nuclei was measured. Three cuts of the preparations of the testes were randomly selected from each individual. In each of them 5 fields with an area of 200 μm^2 were selected. The number of cells of different generations was counted in these fields.

In branchial apparatus of each fish, 5 fields of filaments were selected on one cut. The following measurements were taken on them: the width of respiratory lamellae (proximal, medial, and distal sides) in μm, the number of mucous cells in 1 mm^2, the number of layers of intercalated epithelium cells. Proportion of branchial pathologies of various types was measured on the histological cut. Then, index of organ pathology was calculated according to the formula, the essense of which is summing of

I. S. Nekrasov, A. G. Selyukov
"Size-age and histomorphological indicators of the Arctic grayling (*Thymallus arcticus*) of Putorana Nature Reserve". P. 117.

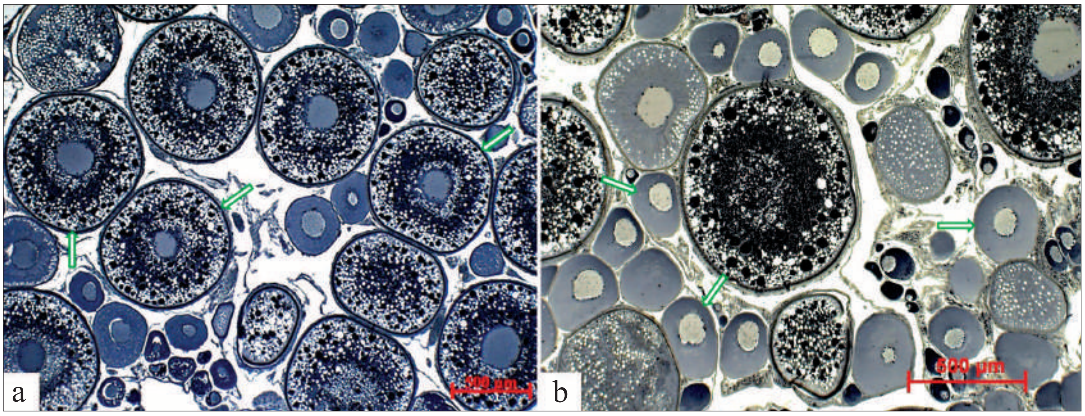

Fig. 1. Ovary of the Arctic grayling, stage III of maturity, the Irkinda river
a – the older generation is represented by vitellogenic oocytes in the yolk accumulation phase (the arrows); b – numerous previtellogenic oocytes (the arrows). Dye: Heidenhain iron hematoxylin

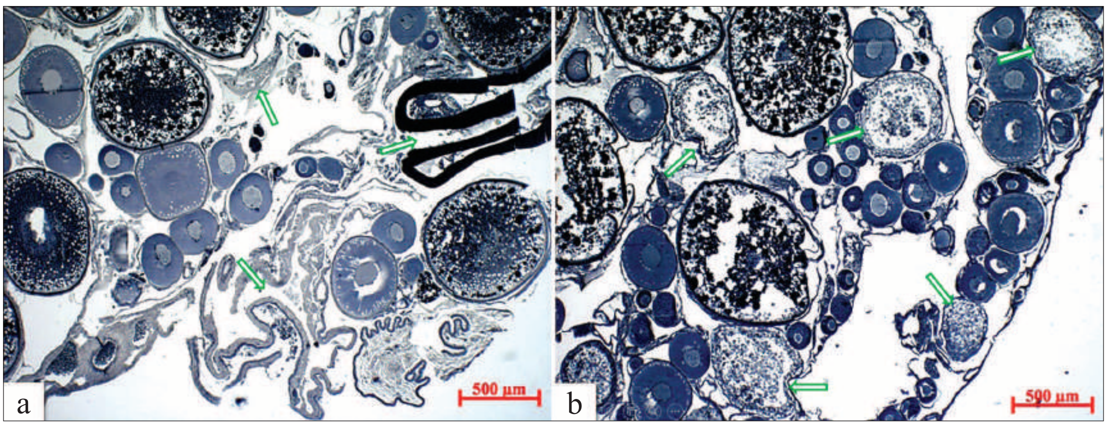

Fig. 2. Vitellogenic oocytes of the Arctic grayling of the Putorana plateau
a – traces of the past spawning in the form of empty follicles (the arrows);
b – multiple atresia of vitellogenic oocytes (the arrows). Dye: Heidenhain iron hematoxylin

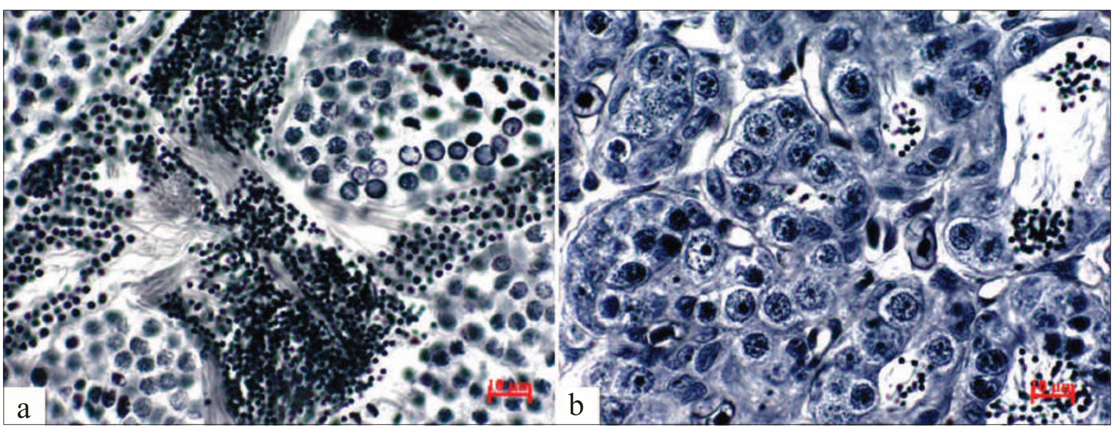

Fig. 3. Typical testes state of the Arctic grayling of the Putorana plateau
a – a testis section of a sexually mature male; there are order I spermatocyte cysts among numerous spermatozoa and spermatids; b – the bulk of germ cells is represented by A- and B-type spermatogonia in an immature male; there are some single spermatids in the lumen of the seminiferous tubules. Dye: Heidenhain iron hematoxylin

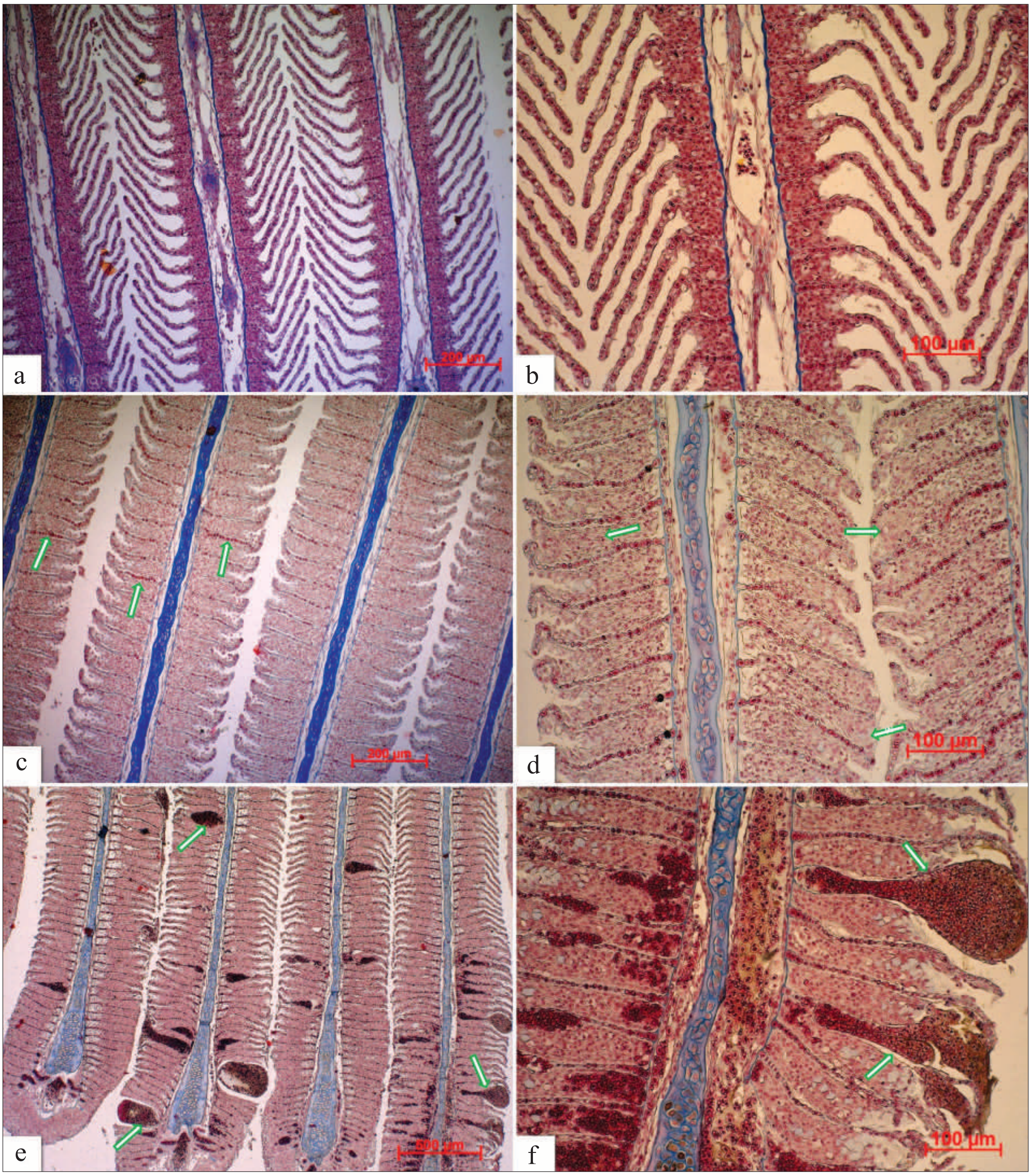

Fig. 5. Gill apparatus of the Arctic grayling of the Irkinda river of the Putorana plateau: a – normal state of the branchial apparatus; b – normal state at higher magnification; c – hyperplasia, hemolysis of erythrocytes (the arrows); d – also at a higher magnification, fusion and increase in intercalary epithelium (the arrows); e – numerous aneurysms (the arrows); f – hemostasis of respiratory lamellae (the arrows). Dye: adhan according to Heidenhain

the shares of each pathology, multiplied by the significance coefficient [16]:

$$I_{pat} = \sum_{pat1}^{pati} \frac{S_{pati}}{S_{org}} \cdot C_{sign},$$

where I_{pat} – index of gill pathology; S_{pati} – area of the pathology; S_{org} – area of the studied zone; C_{sign} – significance coefficient $1 \le C_{sign} \le 3$.

Results and Discussion

Fish of older age groups predominated in the catches (Table 1), among which males predominated (sex ratio 1.8 : 1). The oldest age group was fish of eight years age. Their gonadosomatic index (GSI) was increasing with age. This indicator reflected a relatively large ovarian mass. Most of the fish were sexually mature and had been preparing for the next spawning season. According to results of the histological analysis, Arctic graylings of both sexes in the Irkinda river sexually mature at the age of 6. The largest proportion of females ready for spawning was noted at the age of seven (6+).

Gonads. The ovaries in the majority of sexually mature individuals of the Arctic grayling of the Irkinda river were at maturity stage III, in which vitellogenic oocytes in the yolk accumulation phase were the oldest generation of germ cells (Fig. 1a, see color insert V). The next generation of germ cells is represented by vitellogenic oocytes in cytoplasm vacuolization phase. The next generation was numerous previtellogenic oocytes of different size groups (Fig. 1b, see color insert V).

According to the histological analysis results, ovaries of the majority (67%) of females had traces of the past spawning in the form of degenerating empty follicles among vitellogenic oocytes (Fig. 2a, see color insert V). However, in 83% of females, most of vitellogenic oocytes in cytoplasm vacuolization phase were in the process of resorption (Fig. 2b, see color insert V).

Analysis of the germ cells at different stages of oogenesis showed (Table 2) that in females of different ages, the sizes of oocytes at similar phases veraciously did not differ ($p > 0.05$) or varied insignificantly.

Testes of the most of males were at maturity stage III. Spermatids and sperm were accumulated in seminiferous tubules. Spermatids, sperm, and spermatocytes of the order I were present in the greatest amount in almost all the individuals (Fig. 3a, see color insert V). In immature fish in 3+– 4+, the bulk of germ cells was represented by spermatogonia and spermatocytes (Fig. 3b, see color insert V).

All the types of cells were present in testes of most of the males, but the amount of sperm

Table 1

Biological parameters of the Arctic grayling of the Irkinda river of the Putorana plateau

Parameters	Sex	Age, years			
		3+ – 4+	5+	6+	7+
Smith length, mm	♀	–	318.7±1.3 316–320 (*n* = 3)	341.8±3.0 333–350 (*n* = 6)	350±8 334–359 (*n* = 3)
	♂	285.6±3.4 276–295 (*n* = 5)	325±4 315–332 (*n* = 4)	364±5 348–379 (*n* = 7)	370±4 362–386 (*n* = 5)
Body mass, g	♀	–	349±12 333–373 (*n* = 3)	421±7 393–438 (*n* = 6)	454±21 418–492 (*n* = 3)
	♂	232±7 208–249 (*n* = 5)	369±20 314–409 (*n* = 4)	497±18 424–548 (*n* = 7)	538±12 514–579 (*n* = 5)
GSI, %	♀	–	0.84±0.15 0.61–1.13 (*n* = 3)	1.99±0.12 1.51–2.31 (*n* = 6)	2.51±0.20 2.16–2.84 (*n* = 3)
	♂	0.17±0.01 0.14–0.19 (*n* = 5)	0.79±0.26 0.32–1.31 (*n* = 4)	1.44±0.09 1.10–1.89 (*n* = 7)	1.35±0.07 1.18–1.60 (*n* = 5)

Note. In this table and in the tables 2, 3 the following legend is used: above the line – the average value and its error, below the line – min–max, n – the number of studied fish, "– " – lack of data.

Table 2

Generative indicators of different age groups of the Arctic grayling

Parameters				Oocyte diameter, μm	Nuclei diameter, μm
Age, years	5+ (n = 3)	Previtellogenic oocytes		295±8 283–311	128.3±0.9 126–129
		Vitellogenic oocytes of the cytoplasm vacuolization phase		520±40 459–599	187±16 167–218
	6+ (n = 6)	Previtellogenic oocytes		298±4 287–315	130.1±2.5 122–137
		Vitellogenic oocytes	cytoplasm vacuolization phase	487±8 468–513	191±6 168–202
			yolk accumulation phase	926±20 861–986	235±6 211–251
	7+ (n = 3)	Previtellogenic oocytes		299±5 288–305	123.8±2.2 119–126
		Vitellogenic oocytes	cytoplasm vacuolization phase	522±21 493–563	173.7±3.2 168–179
			yolk accumulation phase	945±36 874–987	235.6±3.8 229–242

was increasing with age due to entry of young generations into meiosis (Fig. 4).

Branchial apparatus. Comparing to the other organs, gills (Fig. 5 a, b, see color insert VI) are highly reactive. This is why even a slight change in hydrochemical regime of the waterbody can cause an adaptive-compensatory restructuring in a very short period of time, which leads to violation of the structure and functioning of the whole organ. Most of the studied fish were diagnosed with pathologies of various nature and depth. The most common ones are cytolysis and thickening of respiratory lamellae (Fig. 5 c, d, see color insert VI). Number of pathologies and their proportion increase with age. In seven years age fish, pathologies such as aneurysms and fusion of the respiratory lamellae appear clearly in addition to the aforementioned deviations (Fig. 5 e, f, see color insert VI).

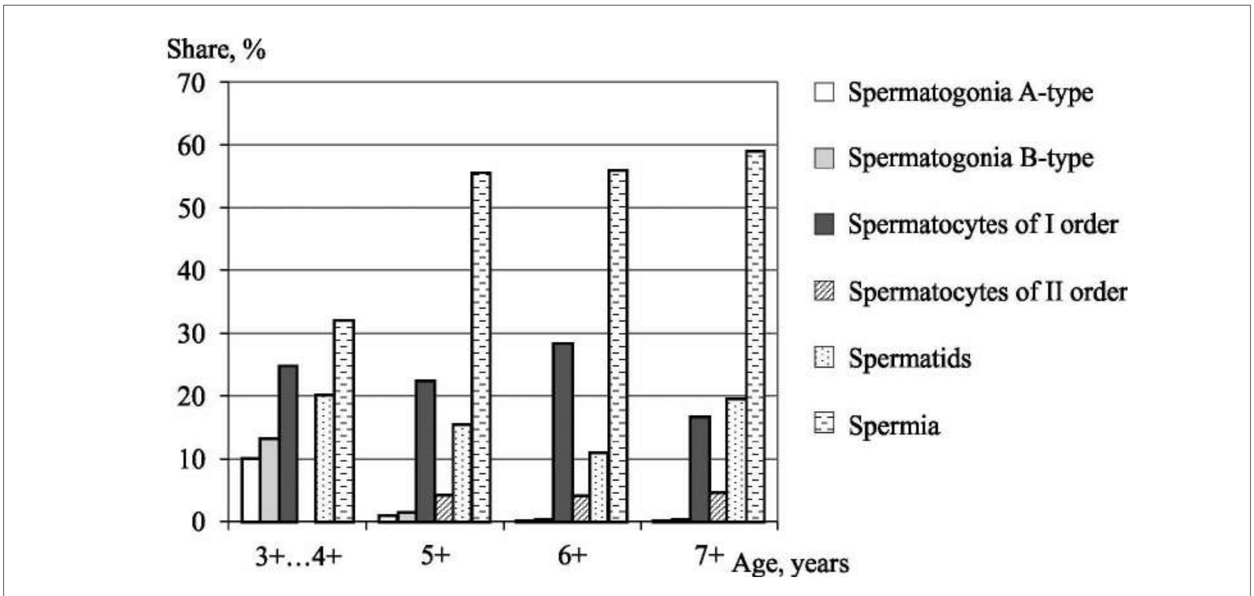

Fig. 4. Ratio (%) of reproductive cells in testes of the Arctic grayling of different age groups (the Irkinda river)

Table 3

The main cytometric characteristics of the branchial epithelium of the Arctic grayling of the Irkinda river of the Putorana plateau (August, 2016)

Age, years (*n*, copies)	Parameters			
	number of layers intercalary epithelium cells	respiratory lamella width, μm	number of mucous cells per 1 mm^2	index of pathology, %
4+ (*n* = 4)	8.3±0.8 6.9–9.7	15.7±0.2 15.4–16.1	266±102 157.1–468.9	0.07±0.01 0.06–0.10
5+ (*n* = 6)	7.9±0.6 6.9–10.1	16.0±1.1 14.0–21.5	252±23 176.4–322.1	0.10±0.02 0.06–0.16
6+ (*n* = 7)	10.8±2.1 7.8–15.0	16.8±1.9 14.7–20.8	233±20 212.6–271.9	0.05±0.02 0.03–0.10
7+ (*n* = 5)	9.4±0.6 8.0–10.9	18.0±0.9 15.8–20.2	240±16 207.4–272.1	0.19±0.05 0.07–0.31

Frequency of occurrence and variety of disorders of the branchial epithelium increased with age, which is reflected in the index of pathology (Table 3). This trend is also true for such cytometric indicators as thickness of respiratory lamellae and number of layers intercalary epithelium cells.

6–7-year-old individuals of both sexes were dominated in the catches. According to the study, the size-mass indicators of the Arctic grayling of the Irkinda River are comparable with the literature data for other waterbodies of Siberia [17–20], which indicates a sufficient food base of the waterbody, despite the extreme living conditions.

According to results of the histological analysis, the Arctic grayling of the Irkinda River sexually matures at the age of 5+, but seven years age individuals made up the majority of sexually mature fish. The oldest generation of germ cells in the ovaries were vitellogenic oocytes in yolk accumulation phase. The reproductive potential is represented by numerous previtellogenic oocytes of different size groups, which indicates a high reproductive potential of the fish [4, 5, 21]. Though, resorption of vitellogenic oocytes in the phase of cytoplasm vacuolization was noticed in the majority of females (83%). With an insignificant proportion of resorbed oocytes in cytoplasm vacuolization phase, such processes can be considered as a norm [22, 23]. This is the phenomenon that was noted in 67% of females of the Arctic grayling of the Irkinda river, which had spawned this year and had been preparing for spawning next year.

We assume that the noted phenomenon reflects an insufficient level of hormones responsible for full-fledged vitellogenesis of all the sex cells entered the hormone-dependent period. The older generations of oocytes intercept estrogens, hereby preventing their entry into the oocyte follicles in the cytoplasm vacuolization phase. Nevertheless, state of the ovaries allows to consider that these females were able to take part in the upcoming spawning.

Testes of the most sexually mature individuals were at maturity stage III. Based on results of the histological analysis, we can confidently state that all the males took part in the past spawning. Reproductive dysfunctions were not found in males. According to the obtained data, individuals of the Arctic grayling had a high level of reproductive activity in the post-spawning period, in spite of low average annual temperatures in the subarctic region.

The branchial apparatus, along with gas exchange and water-salt metabolism, performs a barrier function in the fish organism and has the highest reactivity comparing with other organs, for it responds the most quickly to changes of the hydrochemical regime [24, 25]. Analysis of the gill apparatus state is often used to assess the morphofunctional status of fish [6, 7, 26–29] as the highest trophic link of freshwater ecosystems. Based on the obtained data, it can be claimed that the identified deviations of the branchial apparatus state in the Arctic grayling of the Irkinda river are caused by influence of some kind of unfavorable factor(s). At the same time, no sex specificity in the manifestation of these pathologies was found.

Conclusion

In general, according to the results of the study of the Arctic grayling of the Irkinda River, some deviations in the gonads of females were noticed. At the same time, significant anomalies were revealed in individuals of both sexes in the functioning of their respiratory system. Consequently, aerotechnogenic pollution and pollutant deposits from industrial enterprises of Norilsk city occur even in a mountainous, hard-to-reach protected area [30]. In addition, Ershov [31] described an increased content of lead in soils of Kutaramakan Lake area, where this river eventually flows into. This phenomenon is caused not by technogenic reasons, but by the parent (ore-producing) metallogenic rock. Thus, the revealed pathological changes are the result of both natural and anthropogenic influences.

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