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Structural Analysis of Some Spring Wheat Genotypes Having Genetic Resistance to *Puccinia Recondita*

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Abstract

This study aimed to evaluate the structural development of the main stem and spike productivity elements in a number of spring bread wheat (Triticum aestivum L.) varieties and lines that carry introgressed chromosomal segments from related species associated with genetic resistance to leaf rust (Puccinia recondita). This study included thirteen varieties developed using introgressive breeding, in which resistance genes (Lr) were introduced from different wheat species, and they were tested under the conditions of the 2023 growing season in the Saratov region. The results of the structural analysis showed a clear genetic variation among the studied genotypes in the morphological traits of the stem and spike productivity elements, reflecting differences in the degree of balance of morphogenetic processes during the stages of spike formation, flowering, and grain filling. The results indicated that most genotypes were characterized by an imbalance in the morphogenetic system of spike productivity elements, whereas only one variety was distinguished by possessing a balanced morphogenetic system, indicating higher developmental stability. The morphogenetic productivity index (MPI) proved its effectiveness as a criterion for evaluating spike productivity, through which varieties with genotypes more tolerant to dry environmental conditions were distinguished. These results confirmed the importance of introgressive breeding in enhancing wheat resistance to leaf rust, and also support the adoption of structural analysis and the morphogenetic productivity index as effective tools in wheat breeding programs.

Keywords: Spring wheat, Variety, Structural analysis, Morphogenetic index.

التحليل الهيكلي لبعض الطرز الجينية للقمح الربيعي التي تحمل جينات مقاومة لفطر لـ Puccinia Recondita

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الخلاصة

هدفت هذه الدراسة إلى تقييم التطور البنيوي للساق الرئيسية وعناصر إنتاجية السنبلة في عدد من أصناف وخطوط قمح الخبز الربيعي (Triticum aestivum L.)، والتي تحمل مقاطع كروموسومية مدخلة من أنواع قريبة، ومرتبطة بالمقاومة الوراثية لمرض الصدأ البني (Puccinia recondita). شملت الدراسة ثلاثة عشر صنفًا تم تطويرها باستخدام التربية الإدخالية، حيث أُدخلت جينات المقاومة (Lr) من أنواع مختلفة من القمح، وتم تقييم هذه الطرز الوراثية تحت ظروف موسم النمو لعام 2023 في منطقة ساراتوف. أظهرت نتائج التحليل الهيكلي وجود تباين وراثي واضح بين الطرز الوراثية المدروسة في الصفات المورفولوجية للساق وعناصر إنتاجية السنبلة، مما يعكس اختلاف درجة توازن العمليات المورفوجينية خلال مراحل تكوين السنبلة والإزهار وامتلاء الحبوب. وبينت النتائج أن معظم الطرز الوراثية اتسمت بعدم التوازن في النظام المورفوجيني لعناصر إنتاجية السنبلة، في حين تميز صنف واحد فقط بامتلاكه نظامًا مورفوجينيًا متوازنًا، مما يدل على استقرار تطوري أعلى. وأثبت معامل الإنتاجية المورفوجينية (MPI) فعاليته كمعيار لتقييم إنتاجية السنبلة، إذ أتاح تمييز الطرز الوراثية الأكثر تحمّلًا للظروف البيئية الجافة. وتؤكد هذه النتائج أهمية التربية الإدخالية في تعزيز مقاومة القمح لمرض الصدأ البني، كما تدعم اعتماد التحليل الهيكلي ومعامل الإنتاجية المورفوجينية كأدوات فعّالة في برامج تربية القمح.

كلمات مفتاحية: القمح الربيعي، الصنف، التحليل التركيبي، معامل التكوين المورفوجيني.

Introduction

The genus Triticum, which includes bread wheat (Triticum aestivum L.) and durum wheat (Triticum durum Desf.), represents one of the most important food sources for human consumption worldwide (5). However, modern agricultural practices have led to a narrowing of the genetic base of cultivated wheat, resulting in high levels of genetic uniformity across wide spatial and temporal scales (2 and 6). This reduction in genetic diversity has increased the vulnerability of Triticum aestivum cultivars to newly emerging pests and pathogens (5).

Wild relatives of wheat and other cereal species represent valuable sources of genes and alleles that can be exploited to improve wheat performance and adaptability (9 and 18). The transfer of alien genes into cultivated wheat has been achieved through the development of translocation and introgressive lines, some of which carry genes encoding agronomically important traits (4 and 12). As a result, introgressive breeding has enabled the incorporation of beneficial genes from related species, providing complex resistance to various environmental stresses (1).

Leaf rust, caused by Puccinia triticina Erikss. (syn. Puccinia recondita), is one of the most significant diseases affecting both winter and spring wheat in the Russian Federation and many other countries (8). Effective protection of wheat crops against this disease relies largely on increasing the genetic diversity of cultivated varieties through the introduction of resistance genes (Lr genes) (7). Since the 1990s, more than thirteen spring wheat varieties have been developed at the Research Institute of Agriculture of the South-East (Saratov) using introgressions from various cereal species, including wheatgrass (Elytrigia elongata), rye (Secale cereale L.), Aegilops species (A. squarrosa and A. ventricosa), and intermediate wheatgrass (Agropyron intermedium and A. glaucum) (6).

These introgressive varieties have shown a significant increase in resistance to leaf rust (Puccinia recondita) (8). The use of donors carrying new Lr genes or effective combinations of known resistance genes has contributed to stabilizing epiphytotic conditions of brown rust in wheat-growing regions (11 and 13). The identification of Lr genes in these varieties has been successfully performed using molecular marker techniques (11 and 13). While the resistance performance of such varieties has been well documented, the potential effects of alien chromosomal introgressions on plant development and yield formation have received considerably less attention.

Spike productivity in wheat depends on the coordinated development of morphogenetic processes such as spikelet initiation, flowering, and grain filling (10 and 14). The balance among these processes plays a critical role in determining yield stability, particularly under variable and stressful environmental conditions (16 and 17). Structural analysis of the main shoot provides an effective approach for evaluating the development and coordination of spike productivity elements, including the number of spikelets, number of grains, and grain weight (3). However, this approach has rarely been applied to assess wheat genotypes carrying introgressed resistance genes.

Despite extensive studies on the genetic identification and disease resistance performance of Lr genes (7, 11 and 13), limited information is available on how these introgressions influence the morphogenetic development and structural balance of spike productivity elements. Therefore, the main objective of the present study was to analyze the stem and spike development parameters of the main shoot, assess the balance of morphogenetic processes of spike productivity elements, and determine the morphogenetic productivity index as an integrative indicator of yield-forming potential in spring wheat varieties and introgressive lines under field conditions.

Materials and Methods

The research was carried out under field conditions on the breeding crop rotation of the FSBI "FANTS of the South-East" in 2023. It involved 13 varieties and lines (Table 1) obtained in different years by scientists of the Laboratory of Genetics and Cytology of the Research Institute of the South-East and the Ershovskaya experimental stations. The varieties and lines carry alien chromosomal translocations or gene insertions conferring disease resistance, particularly to leaf rust (Lr genes), originating from related species (7).

Table 1: Spring soft wheat Varieties and Genetic Characteristics.

Variety/Line	Alien chromosome/translocation	Gene(s)	Source
L 503	7DS-7DL-7Ae#1L; 1BL-1R#1S	Lr19, Lr26	Elytrigia elongata, Secale cereale
L503 Lr19+Lr26	7DS-7DL-7Ae#1L; 1BL-1R#1S	Lr19, Lr26	Elytrigia elongata, Secale cereale
L 505	7DS-7DL-7Ae#1L	Lr19	Elytrigia elongata
L 505 656/11	Synthetic (CROC/Ae. squarrosa 224)	Synthetic origin	CROC (durum wheat), Aegilops squarrosa
Prokhorovka	1BL-1R#1S	Lr26	Secale cereale
SE 2	7DS-7DL-7Ae#1L	—	Agropyron intermedium, Elytrigia elongata
Belyanka	6D(6Agi) substitution	—	Agropyron intermedium, A. glaucum
Dobrynya	7DS-7DL-7Ae#1L	Lr19	Elytrigia elongata
Dobrynya Lr19 + Lr37	7DS-7DL-7Ae#1L; 2AL·2AS-2MV#1	Lr19, Lr37	Elytrigia elongata, Aegilops ventricosa
Favorite	6D(6Agi) substitution	—	Agropyron intermedium, A. glaucum
Voevoda	6D(6Agi) substitution	—	Agropyron intermedium, A. glaucum
Swan	6D(6Agi) substitution; 7DS-7DL-7Ae#1L	Lr19	Agropyron intermedium, Elytrigia elongata
Alexandrite	7DS-7DL-7Ae#1L	Lr19	Elytrigia elongata

A total of 30 plants were taken from each of three replicates and combined into a group from which 30 were selected using a random sampling method (11). The determination of the morphogenetic productivity index (MPI) for each of the elements, i.e., the number of colossi, the number of grains, and their mass, was done using the formula:

$$MPI = (n1 \times k1 + n2 \times k2... + n5 \times k5)/n1 + n2... + n5$$

where n is the number of plants of the corresponding class of the variation series, and k the class of the variation series (3). Statistical processing of the results was carried out according to (15) using the Excel Pentium 4 software package.

Results and Discussion

According to the results based on the existing rate of seeding (400 plants per 1m2), the main shoot makes a significant contribution to the grain harvest. At the same time, a small number of lateral shoots were noted, some of which were unproductive (Table 2). Their total number was comparable to the number of lateral shoots of spring soft wheat under favorable year conditions.

Under the conditions of the 2023 growing season, significant variability was noted in the studied varieties and lines of wheat in the development of individual morphological structures of the shoot, such as number of leaves, length of the stem and ear, number of spikelets and grains, and their weight (Table 2). The average number of leaves ranged from 6.5 (L 505, L 505 656/11) to 7.2 mm (Favorite), while stem lengths varied from 664 (Prokhorovka) to 897 mm (L 503 Lr 19+26). In most varieties and lines, stem lengths exceeded 800 mm, which, due to the depository function of the stem, provides an advantage in the arid conditions of the Volga region relative to plants with shortened stems. However, the relative lengths of each stem's internode varied significantly between wheat varieties and lines, especially when compared to the 1st-6th internodes (Fig. 1).

Table 2: Productive and unproductive side tillers of spring soft wheat, 2023.

C varieties and lines	Number of tillers	Productive		Unproductive	
		Items	%	Items	%
L 503	1.97± 0.04	1.30± 0.03	66	0.67± 0.02	34
L 503 Lr 19+26	1.47± 0.03	1.10± 0.02	75	0.37± 0.01	25
L 505	2.80± 0.08	2.53± 0.07	90	0.27± 0.01	10
L 505 656/11	2.04± 0.07	1.57± 0.06	77	0.47± 0.02	23
Prokhorovka	1.90± 0.05	1.47± 0.03	77	0.43± 0.02	23
SE 2	2.23± 0.07	1.70± 0.04	76	0.53± 0.02	24
Dobrynya	1.97± 0.04	1.60± 0.04	81	0.37± 0.01	19
Dobrynya Lr 19+37	1.47± 0.03	1.20± 0.02	82	0.27± 0.01	18
Belyanka	1.57± 0.04	1.10± 0.02	70	0.47± 0.01	30
Favorite	1.63± 0.04	1.13± 0.03	69	0.50± 0.02	31
Voivode	1.70± 0.05	1.27± 0.03	75	0.43± 0.02	25
Swan	2.04± 0.07	1.67± 0.05	82	0.37± 0.02	18
Alexandrite	1.80± 0.05	1.57± 0.05	87	0.23± 0.01	13
NSR 0.95	0.06	0.04		0.02	

The lengths of the ears ranged from 71.4 (L 505 656/11) to 87.8 mm (Prokhorovka). Considering that this parameter depends on the activity of meristem proliferation during the initiation and development phases of the generative shoot phytomers, subsequent breeding works should address the morphogenesis of wheat lines and varieties during the germination phenophase, i.e., tillering of plants. The number of spikelets of an ear is a rather conservative trait that is difficult to change in breeding work. Among the studied varieties and lines of wheat, the number of spikelets ranged from 13.77 (Dobrynya LR 19+37) to 17.4 mm (Prokhorovka) while the number of grains per ear reached 26.7 (Belyanka) to 40.83 (YuV 2) pieces (Table 3).

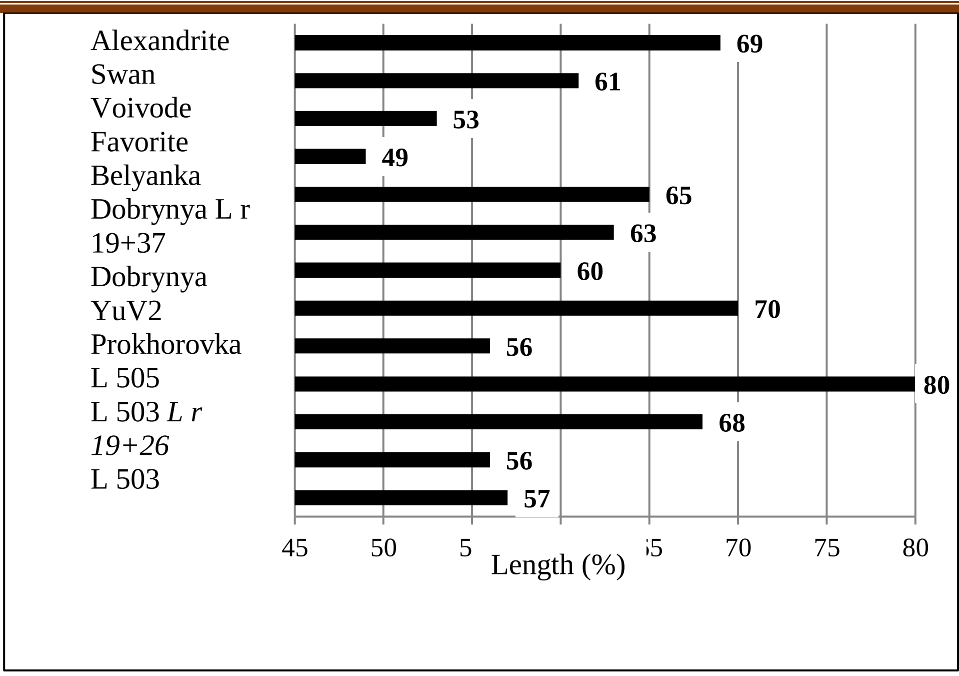

Fig. 1: Lengths and percentages of the 1st-6th internodes of the spring soft wheat stems.

Grain mass is a comprehensive indicator of the balance of morphogenetic and photosynthetic processes in various vegetation conditions. For breeders, the degree of grain filling and the weight of the grain is one of the determining criteria in selecting a particular line of wheat. During the 2023 growing season, grain weights varied from 27.4 (L 505 656/11) to 34.8 (L 503) mg (Table 3).

The balance of morphogenetic processes between the elements of ear productivity is one of the criteria for the yield of a variety (14 and 16). In analyzing crop structure, the location of the variation curves of the ear productivity elements allows an assessment of the balance of morphogenesis at the spikelet formation, flowering, and grain filling stages. The variational curves of the ear productivity elements are classified as balanced when their maximum values fall on one higher class line or variety of wheat (10).

Table 3: Morphological structure of the main shoot of the Saratov wheat varieties and lines, 2023.

C varieties and lines	Stem length (mm)	Ear length (mm)	Number of spikelets	Number of grains	Grain weight (mg)
L 503	873±28	79.6±3.0	14.17±0.38	31.23±0.67	34.8±1.2
L 503 L r 19+26	897±31	83.2±3.2	14.09±0.,63	30.00±0.84	32.8±1.2
L 505	841±34	71.7±3.0	14.77±0.39	32.80±0.90	30.1±1.1
L 505 656/11	779±35	71.4±2.9	13.90±0.57	30.27±1.21	27.4±1.4
Prokhorovka	664±25	87.8±3.1	17.14±0.28	36.50±1.19	31.9±1.4
SE 2	708±31	87.0±3.0	14.97±0.34	40.83±0.92	27.4±1.5
Dobrynya	818±28	74.1±2.8	14.33±0.18	29.80±1.10	30.7±1.5
Dobrynya L r 19+37	844±34	74.9±2.7	13.77±0.18	26.97±1.09	33.0±1.3
Belyanka	847±30	76.8±3.0	14.50±0.26	26.70±0.89	31.0±1.3
Favorite	872±23	87.6±3.2	15.53±0.34	32.90±1.51	30.0±1.1
Voivode	852±29	79.9±2.8	14.86±0.29	29.07±0.93	29.0±1.2
Swan	862±24	80.9±2.7	15.20±0.28	28.43±0.94	34.7±1.5
Alexandrite	853±31	81.1±2.8	15.83±0.28	27.40±1.10	31.6±1.5
NSR 0.95	29	3.0	0.32	1.09	1.4

As shown, 12 of the 13 varieties studied belonged to varieties of spring soft wheat with unbalanced types of morphogenetic systems in terms of ear productivity, number of spikelets, number of grains and their weight. In particular, for the Favorite variety, the maximum values of these characteristics can be observed in different classes of the variation series (Fig. 2). Only in the YuV 2 variety could the maximum of ear productivity elements be noted in one class 3 (Fig. 3), making it possible to classify this variety as a balanced type.

However, the method of structural analysis of wheat shoots has not been widely used in their breeding practices, since the assessment of the balance of the variety in various growing conditions does not allow a determination of potential yield (17). A more useful and applicable criterion for breeding the morphogenetic potential of a variety and, consequently, its yield is the morphogenetic index of productivity (MPI) for each of the elements of spike productivity, i.e., the number of spikelets and grains, and their mass (3).

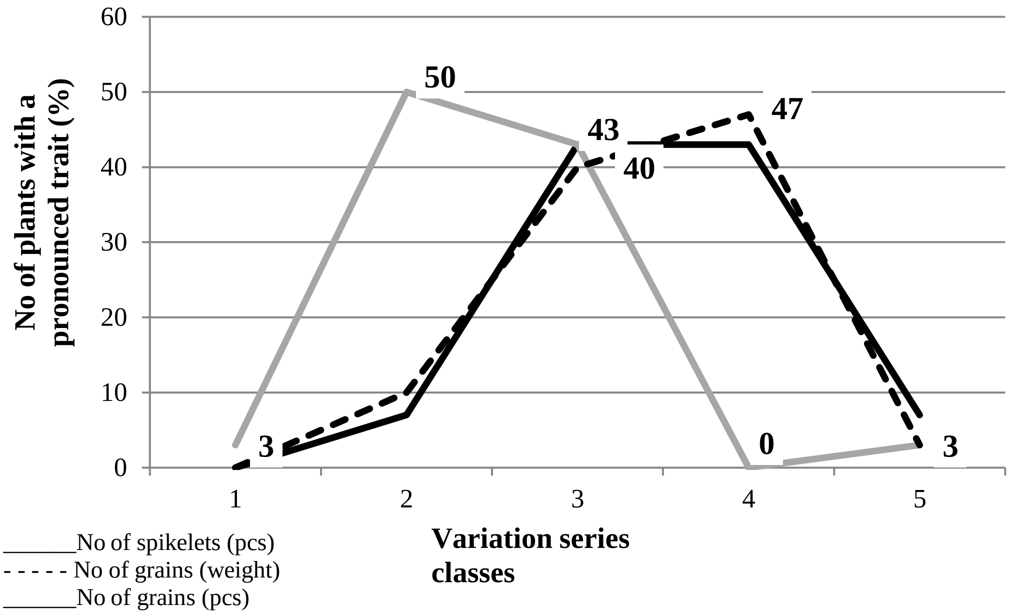

Fig. 2: Variation curves of spike productivity elements of the Favorite spring soft wheat variety, 2023.

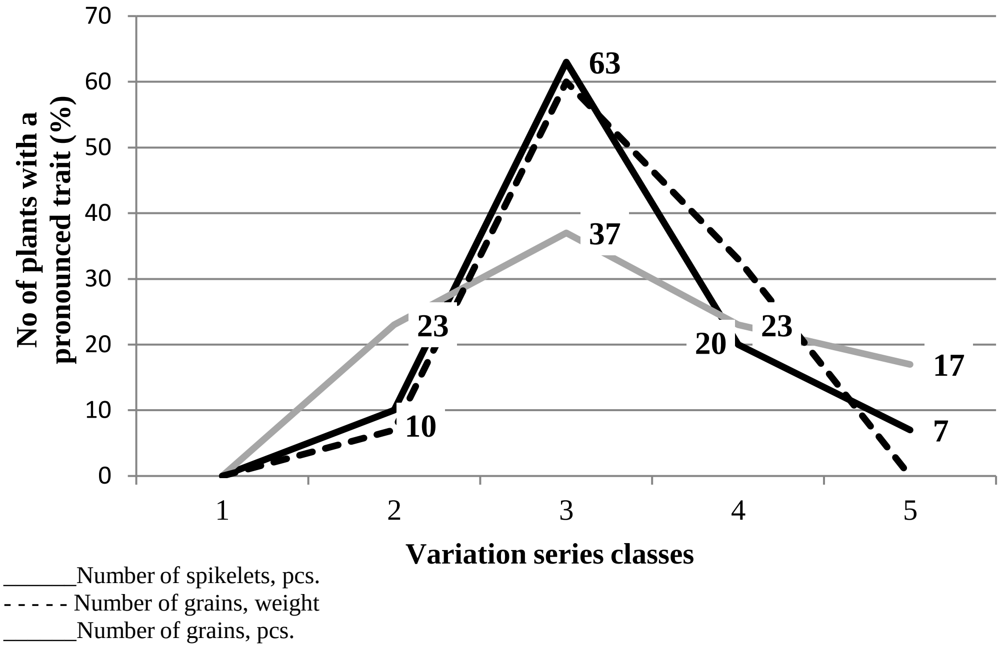

Fig. 3: Variation curves of spike productivity elements of the YuV 2 spring soft wheat variety, 2023.

Under the 2023 growing season conditions, the morphogenetic productivity index for the number of grains varied among the varieties and lines from 2.63 (L505 656/11, Dobrynya Lr19 + lr37) to 4.3 (Prokhorovka). For number of grains, the MPI reached 1.87 (Alexandrite) to 3.33 in YuV 2, while that for mass ranged from 3.23 (L505 656/11) to 3.97 (Lebedushka). The smaller MPI difference in grain weight between wheat varieties and lines indicates that the depositing function of the stem during the period of its active growth makes it possible to subsequently ensure good grain filling (Table 4).

Table 4: Morphogenetic productivity index of the spring wheat varieties, 2023.

Varieties and lines	Number of spikelets	Number of grains	Weight of grains	Average
L 503	2.80	2.43	3.87	3.03
L 503 Lr 19+ lr 26	2.82	2.23	3.80	2.95
L 505	3.10	2.47	3.47	3.01
L505 656/11	2.63	2.60	3.23	2.82
Prokhorovka	4.30	2.90	3.63	3.61
SE 2	3.23	3.33	3.27	3.28
Dobrynya	2.90	2.20	3.57	2.89
Dobrynya Lr19 + lr37	2.63	3.03	3.73	3.13
Belyanka	3.27	1.93	3.57	2.92
Favorite	3.30	2.37	3.43	3.03
Voivode	3.13	2.17	3.37	2.89
Swan	3.37	2.17	3.97	3.17
Alexandrite	3.73	1.87	3.67	3.09
Average	3.17	2.44	3.58	3.06

The limiting factors in the productivity of the varieties were unfavorable climatic conditions during the tillering and formation of the rudimentary ear, as well as at the time of wheat flowering and subsequent development of the grain. This led to a significant difference in the MPI of the number of spikelets and the number of ear grains, the weight of the grain varieties and lines of spring soft wheat.

Conclusions

Morphological differences in wheat lines and varieties under current agroclimatic conditions reflect genotypic characteristics, along with resistance to rust, which contribute to the optimal manifestation of morphogenesis processes. A structural analysis of spring wheat shoots and construction of variation curves of productivity elements allows for a retrospective assessment of the balance of morphogenetic processes during the formation of the generative part of the shoot, flowering, and grain filling. The morphogenetic productivity index can serve as a convenient criterion for breeders to determine the potential yield of a line or variety.

Supplementary Materials:

No Supplementary Materials.

Author Contributions:

M. J. Aljozary: methodology, writing - original draft preparation; S. A. Stepanov and M. Y. Kasatkin: writing - review and editing. All authors have read and agreed to the published version of the manuscript.

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The study was conducted following the protocol authorized by the Head of the Ethics Committee, National Research Saratov State University, Russian Federation.

Informed Consent Statement:

Not applicable.

Data Availability Statement:

Data available upon request.

Conflicts of Interest:

The authors declare no conflict of interest.

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