THE EFFECTIVENESS OF GROWTH-FRIENDLY SYSTEMS IN THE TREATMENT OF EARLY ONSET SCOLIOSIS: A SYSTEMATIC REVIEW

Yu.V. Molotkov[1], S.O. Ryabykh[2, 3], E.Yu. Filatov[1], O.M. Sergeenko[1], I.E. Khuzhanazarov[4, 5], D.I. Eshkulov[5]
[1]Russian Ilizarov Scientific Center for Restorative Traumatology and Orthopaedics, Kurgan, Russia
[2]Pirogov Russian National Research Medical University, Moscow, Russia
[3]St. Petersburg University, St. Petersburg, Russia
[4]Tashkent Medical Academy, Tashkent, Uzbekistan
[5]Republican Specialized Scientific and Practical Medical Center for Traumatology and Orthopedics, Tashkent, Uzbekistan

Objective. To perform a systematic analysis of the literature evaluating the effectiveness of growth-friendly systems in the treatment of early onset scoliosis.

Material and Methods. A subject search was conducted in the Google Scholar database for the terms “growing rods”, “early onset scoliosis”, “treatment”, “surgery” and “growth-friendly” using AND or OR logical operators with a search depth of 10 years. At the first stage, 824 abstracts of publications were selected. The second stage of search was carried out in accordance with the PICOS criteria, 38 abstracts of original studies, case series and reviews of surgical techniques for spinal deformity correction with preservation of growth potential were selected. The evaluation criteria were divided into four groups: general data, correction of the frontal and sagittal components of the deformity, complications and unplanned scenarios.

Results. In the analyzed studies, gender equality of distribution was observed, and the average age at the time of the primary operation was 6.6 years for patients with traditional growing rods (TGR) and Schilla/Luque trolley and 4.9 years for patients with Vertical Expandable Prosthetic Titanium Rib (VEPTR). From the point of view of the magnitude of spinal deformity correction, the VEPTR systems demonstrated the minimum result (18 % correction), and the TGR and Schilla results were comparable (42.1 and 53.1 %, respectively), as well as the indicators of the dynamics of body lengthening.

Conclusion. The use of VEPTR systems is associated with a high risk of complications and a somewhat lower efficiency of spinal deformity correction, however, VEPTR is indispensable in the treatment of thoracic insufficiency syndrome, as well as severe deformities of the axial skeleton in young children using non-vertebral fixation points. Growth modulation systems (Schilla and Luque trolley) showed deformity correction results similar to those of TGR.

Key Words: early-onset scoliosis, growth-friendly systems, complications, efficiency.

Please cite this paper as: *Molotkov YuV, Ryabykh SO, Filatov EYu, Sergeenko OM, Khuzhanazarov IE, Eshkulov DI. The effectiveness of growth-friendly systems in the treatment of early onset scoliosis: a systematic review. Hir. Pozvonoc. 2023;20(2):6–20. In Russian.*

DOI: http://dx.doi.org/10.14531/ss2023.2.6-20.

The concept of “early scoliosis” or “early-onset scoliosis” unites a wide range of spinal deformities occurring in children under the age of 10 years. Depending on the etiology, scoliosis with early onset is usually divided into idiopathic, congenital, neurogenic and systemic [1, 2].

Regardless of the etiology, the course of scoliosis with an early onset is usually rapid, significantly reducing the patient’s quality of life, typically due to severe functional impairment.

The treatment approaches for scoliosis with early onset ranges from orthotics methods [3] to modern remotely expandable spinal implants. The number of papers (more than 1,100 since 1968, according to PubMed, with an increasing annual trend of more than 10 %, and there are 148 papers just in 2021) confirms the disputable nature of their usefulness and therefore their choice and defines the motivation of the authors.

While treating scoliotic deformities in modern pediatric vertebrology, first of all, non-surgical therapy is favorably used, and only when it is ineffective, a decision is made on surgical treatment. The angle of the main deformity curve of more than 40° according to Cobb and the progressive course of the disease are indications for surgical treatment. The mobility of the main and secondary curves and the presence and degree of torsion of the vertebrae are also considered. In every particular case, the final decision on therapy is taken by an attending physician and depends on various factors.

The fundamental principle behind all surgical procedures is spinal deformity correction with preservation of growth potential. This approach provides an opportunity to start treatment at an early age, whereby it is possible to maintain or improve the parameters of the chest volume and ventilation parameters of the lungs by managing the progression of deformities of the spine and chest.

There are two basic surgical techniques in treating extended spinal deformities in children with growth potential: modelling spine growth and using self-expanding systems or those expanding with the assistance of external factors during spine growth. In the first case, the most common procedures are as follows: installation of anterolateral staples on the vertebral bodies on the convex side (Vertebral Body Stapling, VBS) and mobile connection of the vertebral bodies with screws and flexible cable on the convex side (Vertebral Body Tethering, VBT).

Expandable (growth-friendly) systems can be surgically distractible. Standard design: Traditional Growing Rods (TGR); and unique design: Vertical Expandable Prosthetic Titanium Rib (VEPTR) with the possibility of attachment to the vertebrae, ribs, and pelvis. Moreover, there are growth-friendly systems that do not require lengthening them surgically: the magnetically controlled growing rod (MCGR), the Shilla Growth Guidance System (SGGS), the modern Luque Trolley system (MLT), and other less popular systems with a similar traction mechanism [4–6].

The objective is to perform a systematic analysis of the literature evaluating the effectiveness of growth-friendly systems in the treatment of early-onset scoliosis.

Material and Methods

The strategy of search and analysis of literary data

A search for modern academic literature containing data on the outcomes and effectiveness of treatment of early-onset scoliosis using the traditional growing rods (TGR) technique, the VEPTR system, and spinal growth modulation systems (Schilla and Luque Trolley) was conducted in the format of the designated objective. This review does not include papers on treatment using MCGR. Domestic researchers are unquestionably interested in these implants. Nonetheless, a different (non-invasive) distraction principle requires separate consideration, and the implant's lack of registration and high cost limit its widespread implementation in the Russian Federation. Furthermore, a significant systematic literature review and one meta-analysis on this issue were released in the last year. We reviewed the key data from these sources in the Discussion section [7].

A subject search was conducted in the Google Scholar database for the terms "growing rods", "early onset scoliosis", "treatment", "surgery", and "growth-friendly" using AND or OR logical operators with a search depth of 10 years (from 2012 to 2022). At the first stage, 824 abstracts of publications were selected (Fig.). The second stage of search was done manually in accordance with the inclusion/exclusion criteria and selection of PICOS publications (Table 1) [8].

Upon meeting the above criteria and analyzing the titles, abstracts, and full texts, 38 original articles from peer-reviewed scientific journals were selected and included in the analysis. Several techniques are discussed simultaneously in nine articles, respectively. In this regard, we have placed them in several groups.

The number of patients in the reviewed articles varied from 11 to 527 (mean 74.2; total 3,638).

The evaluation criteria. The data collected through the articles chosen on the second search stage were placed in tables that can be conditionally separated into numerous groups:

1) general data (number of patients, gender ratio, mean age at the start of treatment);

2) complications and unplanned scenarios (number of patients with complications, complications associated with implants, correction disorders, infectious complications, neurological complications, other complications, mean number of complications per patient);

3) treatment outcomes: correction of scoliosis (mean values: Cobb angle, T1–S1 distance) and impact on thoracic kyphosis and lumbar lordosis (mean values: Cobb angle).

The percentage of deformity correction at the time of the last follow-up and the loss of deformity correction during the follow-up period were also calculated during the course of the study (if information was available). The last row of each table contains the mean/total values, generalizing the data from the articles under study.

Results

General data on the patient cohort under consideration are given in Table 2; data on deformity correction are shown in Table 3; and complications and unplanned scenarios are presented in Table 4. Table 5 shows summary data from the papers considered on etiological groups.

General data

During the literature review, 27 articles were found describing 2,119 patients with TGR implants; 15 articles with 1,170 patients with VEPTR implants; and 7 articles with 349 patients with Schilla/Luque Trolley systems.

The mean age of patients with VEPTR systems at the time of the primary surgery was 4.90 ± 1.03 years; the mean age of patients with TGR was 6.60 ± 1.45 years with TGR; and the mean age of patients with Schilla/Luque Trolley was 6.60 ± 0.86 years.

The gender ratio was roughly 1:1 in studies dedicated to the Schilla/Luque Trolley and VEPTR systems, but the TGR patient group had a slight predominance of girls (849 boys and 1,114 girls).

On average, patients with TGR underwent 5.30 ± 1.56 planned distractions during treatment, and patients treated with VEPTR underwent 8.50 ± 1.62 planned distractions. Patients with Schilla/Luque Trolley had no planned distractions. The replacement of the growth-friendly system with a rigid instrumentation with the mounting of additional transpedicular support points between the cranial and caudal bases was the final stage of treatment for 680 (32 %) patients with TGR, for 187 (16 %) patients with VEPTR, and for 76

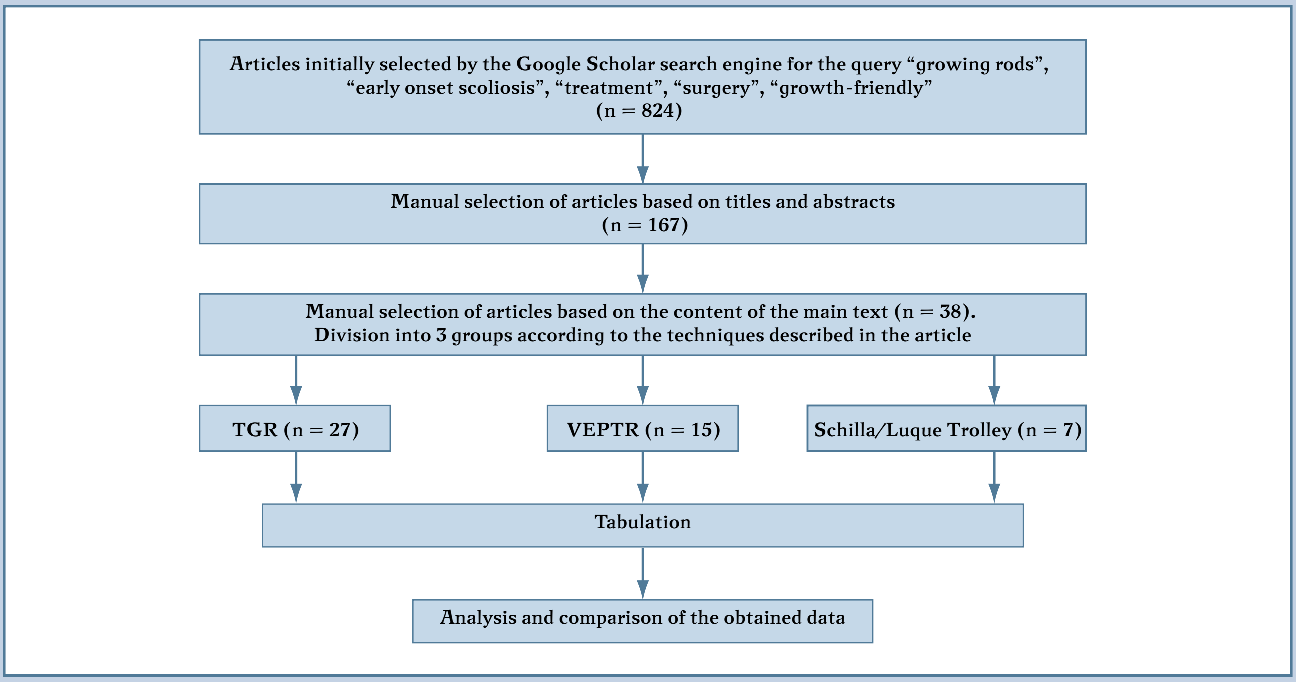

Fig.
Selection of publications for research

(22 %) patients with Schilla/Luque Trolley systems.

The mean follow-up period after the end of treatment (final instrumentation or last distraction) among all patients was 5 years: 4.5 years in the TGR group; 6.6 years in the VEPTR group; and 5 years in Schilla/Luque Trolley. The mean age of patients at the time of the last follow-up is specified in only one article [31] and amounted to 13.4 years.

Distribution by etiological groups

In the group of patients with TGR, idiopathic scoliosis was identified in 27.6 % of the patients, systemic scoliosis in 26.0 %, neurogenic scoliosis in 25.0 %, and congenital scoliosis in 20.6 % of the patients. VEPTR was used in 15.0 % of patients suffering from idiopathic scoliosis, 14.3 % with systemic scoliosis, 35.6 % with neurogenic scoliosis, and 34.8 % with congenital scoliosis. Growth modulation systems were used in the following ratio: 24.7 % of patients with idiopathic scoliosis, 26.4 % with systemic scoliosis, 39.1 % with neurogenic scoliosis, and 9.8 % with congenital scoliosis.

Table 1

Criteria for inclusion/exclusion and selection of publications in accordance with the principles of PICOS

PICOS elements	Inclusion	Exclusion
Participants	Children under 10 years of age who have received surgical treatment for spinal deformities	Patients over 10 years, patients who did not receive surgical treatment for spinal deformity
Intervention	Surgical treatment for early-onset scoliosis using one of the following techniques: TGR, VEPTR, Shilla, Luque Trolley	Surgical treatment using MCGR or VBT or other metal instrumentation. The use of several techniques during the treatment
Comparison	Study groups in selected articles	
Outcome	Radiological parameters, number of complications, clinical outcomes of treatment	
Study design	Non-randomized, retrospective, prospective. Long-term result over two years	Randomized. Lack of data on long-term outcome or follow-up less than two years
Publications	In Russian, English, full text	In any other languages, without access to the full text

Table 2

The structure of the patient's cohort from the literature

Source	Patients, n	Gender (male/female), n	Mean age, years old
TGR			
Xu et al. [9]	27	10/17	6.5
Liang et al. [10]	55	16/39	6.8
Wijdicks et al. [11]	527	191/336	N/A
Helenius et al. [12]	12	N/A	N/A
Zarei et al. [13]	42	22/20	4.8
Jiang et al. [14]	59	24/35	8.9
Wang et al. [15]	30	10/20	7.3
Jain et al. [16]	14	4/10	6.8
Chen et al. [17]	40	N/A	6.3
Arandi et al. [18]	175	62/77	6.0
Luhmann et al. [19]	18	N/A	7.7
Jayaswal et al. [20]	13	6/7	6.8
Chiba et al. [21]	22	4/18	5.0
Bouthors et al. [22]	18	6/12	8.0
Chen et al. [23]	22	16/6	6.4
Yang et al. [24]	95	45/50	6.5
Yehia et al. [25]	15	8/7	8.5
Helenius et al. [26]	214	86/128	5.6
Chang et al. [27]	17	7/10	7.9
Bachabi et al. [28]	50	N/A	5.5
Klyce et al. [29]	396	223/173	6.7
Cobanoglu et al. [30]	46	18/28	N/A
Paloski et al. [31]	46	23/23	N/A
Akbarnia et al. 32	12	5/7	6.5
Upasani et al. [33]	110	49/61	6.3
Larson et al. [34]	16	5/11	5.9
Matsumoto et al. [35]	28	9/19	6.5
Total	2119	849/1114	6.6
VEPTR			
Wijdicks et al. [11]	145	76/69	N/A
Helenius et al. [12]	13	N/A	4.6
Chen et al. [17]	11	N/A	6.8
Waldhausen et al. [36]	65	N/A	6.9
Peiro-Garcia et al. [37]	20	9/11	4.0
Upasani et al. [38]	71	N/A	3.3
El-Hawary et al. [39]	35	18/17	2.7
El-Hawary et al. [40]	63	35/28	6.1
Bachabi et al. [28]	22	N/A	4.3
Studer et al. [41]	34	19/15	7.4
Klyce et al. [29]	390	205/185	6.1
Qiu et al. [42]	60	35/25	4.6
Heflin et al. [43]	12	8/4	6.3
Larson et al. [34]	153	72/81	4.6
Matsumoto et al. [35]	76	32/44	6.2
Total	1170	509/479	4.9
Schilla u Luque Trolley			
Wijdicks et al. [11]	156	82/74	N/A
Luhmann et al. [19]	18	N/A	7.9

Radiographic findings

Most papers only display radiographic findings at the following control points: (1) prior to treatment; (2) following the original operation; (3) after the end of treatment (last instrumentation or last distraction); and (4) during the final observation. The mean preoperative Cobb angle was 71.6° ± 10.2° in the TGR group, 69.5° ± 3.8° in the VEPTR group, and 67.8° ± 5.3° in the Schilla/Luque Trolley group. The mean length of T1-S1 before surgery was 25.2 ± 1.4 cm in the TGR group, 23.1 ± 2.3 cm in the VEPTR group, and 27.7 ± 2.8 cm in the Schilla/Luque Trolley group.

Thoracic kyphosis values according to Cobb before treatment were 50.4 ± 9.6° in the TGR group, 42.0° ± 10.2° in the VEPTR group, and 36.5° ± 8.5° in the Schilla/Luque Trolley group. Lumbar lordosis indications prior to primary surgery: 47.8° ± 9.7° (TGR), 47.7° ± 5.5° (VEPTR), and 26.5° ± 5.0° (Schilla/Luque Trolley).

The correction values of the main scoliotic curve at the end of treatment in patients with TGR were 42.0 ± 7.8%, in patients with Schilla/Luque Trolley were 53.0 ± 16.4 %, and in patients with VEPTR were 18.0 ± 8.6 %.

The loss of correction (the difference between the percentages of correction after primary surgery and final instrumentation) was 1.9 % in the TGR group, 9.1 % in VEPTR, and 13.5 in Schilla/Luque Trolley.

The change in trunk length in patients with TGR was 8.00 ± 1.57 cm, with VEPTR – 6.5 ± 1.2 cm, with Schilla/Luque Trolley – 7.7 ± 2.6 cm.

In the TGR group, thoracic kyphosis was decreased on average by 10.0° ± 7.7° during treatment; in the Schilla/Luque Trolley group – by 4.2° ± 18.7°; while in the VEPTR group, it increased on average by 18.4° ± 14.3°.

In the TGR group, lumbar lordosis increased by 2.9° ± 6.8° according to Cobb during treatment; in patients with VEPTR – by 6.0° ± 4.2°; and in the Schilla/Luque Trolley group – by 10.5° ± 13.4°.

By the end of the follow-up period, the scoliotic deformity correction in the TGR group was 42.4 % (primary: 42.1 %); in the VEPTR group – 18.0 % (prima-

The end of the Table 2

The structure of the patient's cohort from the literature

Source	Patients. n	Gender (male/female). n	Mean age. years old
Schilla u Luque Trolley			
Saarinen et al. [44]	13	8/5	6.0
Luhmann et al. [45]	19	7/12	6.1
Klyce et al. [29]	83	47/36	7.3
McCarthy et al. [46]	40	17/23	7.0
Nazareth et al. [47]	20	10/10	5.7
Total	349	171/160	6.6

N/A — not available.

ry: 25.3 %); in the Schilla/Luque Trolley group – 53.1 % (primary: 63.4 %).

Complications and unplanned scenarios

50 % of patients with TGR had complications, 626 (62 %) of which were implant-associated, 132 (13 %) were infectious, and 31 (3 %) were neurological.

In the VEPTR group, complications were observed in 58 % of patients: 334 (48 %) were implant-associated, 20 (3 %) were infectious, and 6 (0.06 %) were neurological.

In the Schilla/Luque Trolley group, 64 % of patients had the following complications: 69 (79 %) implant-associated, 15 (17 %) infectious.

The impact of surgical treatment on the quality of life of patients

The EOSQ-24 questionnaire was used only in 4 out of 38 studies, and the SRS-24 patient questionnaire was used in one study. This issue was not given any attention in other publications. According to one of the papers, there is no significant difference in the quality of life in patients with VEPTR and TGR systems [23]. There is data suggesting lower preoperative quality of life in patients with skeletal dysplasia than in patients with idiopathic scoliosis. Meanwhile, there was no pronounced positive dynamics in the quality of life in both groups [12]. According to questionnaire results in other articles, there are only slight changes in patients' quality of life, both positive and negative side, depending on different criteria [25, 27, 44].

Discussion

Nowadays, there are many types of instrumentation used for the treatment of early-onset scoliosis based on different mechanical principles. The amount of reported data in the modern academic literature is extremely large, and the data are heterogeneous. In this regard, it is impossible to reveal with full confidence a single gold standard in the treatment of early scoliosis [48].

Vertical Expandable Prosthetic Titanium Rib (VEPTR)

Campbell et al. [49] were the first to introduce VEPTR as a system that can be used for thoracic insufficiency syndrome. In Russia, this technique was applied for the first time in 2008 [50]. VEPTR systems, originally developed for patients with thoracic insufficiency syndrome, are intensively applied to early-onset scoliosis, especially in children in the first two years of life [51]. Their advantage is the possibility of combined expansion thoracoplasty, the mounting of rib-based, spine-based, and pelvis-based anchor points for the installation of distractors "rib-to-rib", "rib-to-spine", and "rib-to-pelvis". Moreover, the mounting of such anchor elements prevents premature loss of transpedicular fixation points prior to the mounting of the final instrumentation due to the malposition of the screws and/or excessive injury to the vertebral pedicles when attempting to install them. This approach simplifies the final instrumentation, provides a greater percentage of correction and improves the treatment outcome. Considering the features of the support and the time of primary implantation, stage distractions are recommended to be performed every 4–6 months.

As a result of the literature analysis, it was revealed that this type of construction was used mainly in very young patients (the mean age of the primary surgery was 4.9 years), mainly in congenital and neurogenic scoliosis (34.8 and 35.5 % of patients, respectively).

Frequently, this technique is used as a preliminary stage before other treatment techniques (TGR, vertebrotomy, etc.). In this regard, the indicated amount of correction loss can hardly be considered a significant outcome. Nonetheless, only 16 % of cases of final fixation of the spine by the rigid instrumentation at the end of treatment were discovered, according to the data provided in the examined studies.

Traditional Growing Rods (TGR)

TGR is the most world widely used treatment technique for early scoliosis [52]. Harrington et al. were the first to propose traditional growing rods in 1962. Akbarnia et al. suggested a modification with the use of double rods.

Traditional growing rods allow to correct scoliotic deformity effectively (mean by 42 %) and control the spinal axis. However, they reduce its mobility, have a comparatively high risk of complications (50%) and also require planned surgeries every 6–8 months to expand the instrumentation. At the primary surgery, the correction with TGR is 30–60%, and traction is done with an interval of 6–12 months.

The literature review on the issue of treating early-onset scoliosis using the TGR approach revealed that this kind of instrumentation has been used in patients with mean age of 6.6 years who had early-onset scoliosis of different etiologies. A distraction connector was removed and final screw fixation was performed only in 32 % of cases when this technique was used in the end of treatment.

Shilla and Luque Trolley

The Shilla system was first reported in 2014 [53]. It involves rigid fixation with fusion, performing a derotation maneu-

Table 3
Summary data on the mean values of the radiological parameters of the analyzed growing systems (according to the literature)

Source	Cobb angle, degrees				T1–S1 extend, cm				Thoracic kyphosis according to Cobb, degrees				Lumbar lordosis according to Cobb, degrees				Distractions, n
	Before treatment	After primary surgery	The last follow-up	Correction, %	Before treatment	After primary surgery	The last follow-up	Correction, %	Before treatment	After primary surgery	The last follow-up	Correction, %	Before treatment	After primary surgery	The last follow-up	Correction, %	
TGR																	
Xu et al. [9]	64.9	32.9	34.5	46.8	26.6	29.2	34.1	7.5	53.1	38.5	40.4	12.7	50.6	42.4	44.9	5.7	5.0
Liang et al. [10]	72.1	N/A	36.1	49.9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	4.3
Wijdicks et al. [11]	72.6	37.6	38.5	47.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Helenius et al. [12]	83.6	N/A	44.9	46.3	22.9	N/A	28.9	6.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Zarei et al. [13]	42.9	N/A	28.8	32.9	N/A	N/A	N/A	N/A	30.3	N/A	17.6	12.7	N/A	N/A	N/A	N/A	N/A
Jiang et al. [14]	91.9	53.5	47.9	47.9	24.8	31.2	35.7	10.9	64.7	36.2	42.7	22.0	60.4	47.0	47.0	13.4	N/A
Wang et al. [15]	72.3	34.9	35.3	51.2	25.4	29.1	33.4	8.0	37.6	26.6	35.1	2.5	51.1	43.3	48.0	3.1	4.2
Jain et al. [16]	73.6	30.2	36.2	50.8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	4.3
Chen et al. [17]	71.4	40.9	46.2	35.3	24.1	26.7	30.7	6.6	51.0	37.6	40.5	10.5	51.5	44.9	44.2	7.3	N/A
Arandi et al. [18]	79.5	41.5	45.5	42.8	25.3	29.4	33.4	8.1	54.5	36.0	47.0	7.5	47.0	42.5	44.0	3.0	5.9
Luhmann et al. [19]	64.6	37.8	35.7	44.7	27.9	32.2	36.9	9.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	5.8
Jayaswal et al. [20]	78.5	57.4	53.1	32.4	22.7	24.9	27.5	4.8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	5.7
Chiba et al. [21]	79.3	34.5	38.4	51.6	24.4	28.0	34.0	9.6	54.0	34.4	44.1	9.9	43.8	39.4	57.2	-13.4	N/A
Bouthors et al. [22]	57.2	N/A	37.0	35.3	26.6	29.2	34.1	7.5	37.0	N/A	33.5	3.5	N/A	N/A	N/A	N/A	3.0
Chen et al. [23]	72.0	46.0	44.0	38.9	24.7	27.8	33.4	8.7	56.0	32.0	38.0	18.0	52.0	45.0	50.0	2.0	6.6
Yang et al. [24]	73.0	36.8	44.6	38.9	24.7	27.8	32.9	8.2	40.2	29.8	34.7	5.5	50.4	45.9	46.9	3.5	4.0
Yehia et al. [25]	73.8	51.7	N/A	N/A	24.6	31.5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2.6
Helenius et al. [26]	84.0	48.0	48.5	42.3	24.5	28.5	33.7	9.2	55.5	37.0	50.0	5.5	23.0	21.5	19.0	4.0	7.4
Chang et al. [27]	65.0	45.0	43.0	33.8	N/A	N/A	N/A	N/A	43.0	47.0	51.0	-8.0	N/A	N/A	N/A	N/A	N/A
Bachabi et al. [28]	78.0	38.0	35.0	55.1	N/A	N/A	N/A	N/A	57.0	38.0	38.2	18.8	N/A	N/A	N/A	N/A	8.5
Klyce et al. [29]	75.0	N/A	34.0	54.7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Cobanoglu et al. [30]	53.0	39.0	39.0	26.4	N/A	N/A	N/A	N/A	64.0	50.0	49.0	15.0	48.0	47.0	48.0	0.0	N/A
Paloski et al. [31]	78.0	N/A	47.7	38.8	27.4	N/A	33.3	5.9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	7.0
Akbarnia et al. [32]	64.0	35.0	42.0	34.4	25.7	30.3	34.2	8.5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	4.6
Upasani et al. [33]	75.5	43.0	48.3	36.0	26.3	30.2	36.3	10.0	55.6	44.0	50.5	5.1	N/A	N/A	N/A	N/A	N/A
Larson et al. [4	61.0	N/A	37.0	39.3	24.1	N/A	32.2	8.1	53.0	N/A	35.0	18.0	N/A	N/A	N/A	N/A	N/A

N/A — not available.

The end of the Table 3

Summary data on the mean values of the radiological parameters of the analyzed growing systems (according to the literature)

Source	Cobb angle. degrees				T1–S1 extend. cm				Thoracic kyphosis according to Cobb. degrees				Lumbar lordosis according to Cobb. degrees				Distractions. n
	Before treatment	After primary surgery	The last follow-up	Correction. %	Before treatment	After primary surgery	The last follow-up	Correction. %	Before treatment	After primary surgery	The last follow-up	Correction. %	Before treatment	After primary surgery	The last follow-up	Correction. %	
TGR																	
Matsumoto et al. [35]	77.3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	49.7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	6.3
Total	71.6	41.2	40.8	42.1	25.2	29.1	33.2	8.0	50.4	37.5	40.5	10.0	47.8	41.9	44.9	2.9	5.3
VEPTR																	
Wijdicks et al. [11]	66.6	46.4	53.8	19.2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Helenius et al. [12]	71.5	N/A	60.0	16.1	20.2	N/A	26.6	6.4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Chen et al. [17]	74.0	50.0	47.0	36.5	24.5	27.4	32.4	7.9	52.0	40.0	64.0	-12.0	54.0	43.0	57.0	-3.0	6.8
Waldhausen et al. [36]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	5.5
Peiro-Garcia et al. [37]	75.0	53.5	N/A	N/A	25.7	27.3	N/A	N/A	42.0	33.0	N/A	N/A	44.5	37.5	N/A	N/A	N/A
Upasani et al. [38]	64.7	54.1	58.5	9.6	21.4	23.0	28.6	7.2	32.7	34.2	46.0	-13.3	44.5	42.0	53.4	-8.9	9.9
El-Hawary et al. [39]	63.5	57.1	N/A	N/A	19.9	22.1	28.0	8.1	40.5	44.5	72.0	-31.5	N/A	N/A	N/A	N/A	9.0
El-Hawary et al. [40]	72.0	47.0	56.6	21.4	24.9	28.6	29.9	5.0	48.0	40.0	48.0	0.0	N/A	N/A	N/A	N/A	N/A
Bachabi et al. [28]	74.0	53.0	57.0	23.0	N/A	N/A	N/A	N/A	21.0	40.0	64.0	-43.0	N/A	N/A	N/A	N/A	9.8
Studer et al. [41]	70.0	50.0	65.0	7.1	N/A	N/A	N/A	N/A	53.0	43.0	70.0	-17.0	N/A	N/A	N/A	N/A	10.0
Klyce et al. [29]	67.0	N/A	53.0	20.9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Qiu et al. [42]	69.2	59.4	N/A	N/A	21.7	N/A	27.1	5.4	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10.0
Heflin et al. [43]	66.3	N/A	60.8	8.3	26.0	N/A	33.0	7.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	7.7
Larson et al. [34]	66.0	N/A	58.0	12.1	23.7	N/A	29.0	5.3	40.0	N/A	52.0	-12.0	N/A	N/A	N/A	N/A	8.0
Matsumoto et al. [35]	73.0	48.6	55.7	23.7	N/A	N/A	N/A	N/A	48.5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Total	69.5	51.9	56.9	18.0	23.1	25.7	29.3	6.5	42.0	39.2	59.4	-18.4	47.7	40.8	55.2	-6.0	8.5
Schilla u Luque Trolley																	
Wijdicks et al. [11]	65.0	26.4	36.0	44.6	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Luhmann et al. [19]	60.6	23.8	33.9	44.1	30.7	34.0	38.4	7.7	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Saarinen et al. [44]	64.0	22.0	12.0	81.3	27.2	30.6	38.6	11.4	45.0	28.0	22.0	23.0	23.0	34.0	43.0	-20.0	N/A
Luhmann et al. [45]	70.3	22.4	40.0	43.1	28.7	N/A	32.9	4.2	36.6	N/A	51.0	-14.4	N/A	57.0	N/A	N/A	N/A
Klyce et al. [29]	69.0	N/A	19.0	72.5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
McCarthy et al. [46]	69.0	25.0	38.4	44.3	N/A	N/A	N/A	7.9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Nazareth et al. [47]	77.0	29.0	45.0	41.6	24.0	29.1	31.3	7.3	28.0	21.0	24.0	4.0	30.0	28.0	31.0	-1.0	N/A
Total	67.8	24.8	32.0	53.1	27.7	31.2	35.3	7.7	36.5	24.5	32.3	4.2	26.5	39.7	37.0	-10.5	N/A

N/A — not available.

Table 4

Summary data on complications and unplanned scenarios (according to the literature)

Source	Patients with complications, %	Implant-associated complications, n	Deformity progression, n	Infectious complications, n	Neurological complications, n	Other complications, n	Mean number of complications per one patient
TGR							
Xu et al. [9]	N/A	6	6	2	N/A	N/A	1.2
Liang et al. [10]	42.0	25	4	4	1	7	0.7
Wijdicks et al. [11]	17.0	0	3	4	N/A	N/A	0.2
Helenius et al. [12]	N/A	60	19	5	3	10	1.3
Zarei et al. [13]	23.3	9	2	N/A	N/A	1	0.4
Jiang et al. [14]	64.3	8	6	2	1	3	1.4
Wang et al. [15]	65.0	16	11	2	N/A	N/A	0.7
Jain et al. [16]	N/A	146	N/A	N/A	N/A	N/A	1.8
Chen et al. [17]	46.0	11	N/A	7	N/A	8	1.4
Arandi et al. [18]	53.0	9	N/A	N/A	2	7	1.2
Luhmann et al. [19]	N/A	3	2	1	0	N/A	0.3
Jayaswal et al. [20]	N/A	17	7	0	N/A	N/A	1.4
Chiba et al. [21]	72.7	6	3	3	N/A	2	0.6
Bouthors et al. [22]	33.3	2	N/A	4	N/A	N/A	N/A
Chen et al. [23]	73.5	124	N/A	29	15	45	2.2
Yang et al. [24]	53.0	8	N/A	6	1	N/A	0.8
Yehia et al. [25]	N/A	13	N/A	N/A	N/A	N/A	N/A
Helenius et al. [26]	79.0	145	N/A	60	7	51	2.4
Chang et al. [27]	N/A	3	N/A	1	N/A	N/A	N/A
Bachabi et al. [28]	32.1	15	N/A	2	1	2	0.7
Total	50.3	626 (63 %)	63 (6 %)	132 (13 %)	31 (3 %)	136 (14 %)	1.1
VEPTR							
Wijdicks et al. [11]	72.7	6	3	3	N/A	2	1.2
Helenius et al. [12]	33.0	35	N/A	9	N/A	1	1.75
Chen et al. [17]	65.0	7	1	2	1	4	1.2
Waldhausen et al. [36]	85.0	90	N/A	97	N/A	N/A	2.6
Peiro-Garcia et al. [37]	49.0	15	5	6	1	30	1.1
Upasani et al. [38]	82.0	15	N/A	9	N/A	2	1.0
El-Hawary et al. [39]	N/A	45	N/A	19	N/A	N/A	1.9
El-Hawary et al. [40]	40.0	16	10	69	N/A	5	2.5
Bachabi et al. [28]	66.0	8	1	N/A	N/A	5	1.4
Studer et al. [41]	N/A	71	N/A	30	N/A	N/A	1.5
Klyce et al. [29]	31.6	26	N/A	15	4	22	1.1
Total	58.3	334 (48 %)	20 (3 %)	259 (37 %)	6 (0.01 %)	71 (10 %)	1.6
Schilla и Luque Trolley							
Wijdicks et al. [11]	N/A	13	N/A	5	N/A	1	1.1
Luhmann et al. [19]	38.0	8	N/A	1	N/A	1	0.7
Saarinen et al. [44]	68.4	1	N/A	3	N/A	1	0.2
Luhmann et al. [45]	73.0	47	N/A	6	N/A	N/A	1.3
Klyce et al. [29]	75.0	26	N/A	1	N/A	2	1.4
Total	63.6	69 (79 %)	N/A	15 (17 %)	N/A	3 (3 %)	0.94

N/A — not available.

Table 5

Distribution of patients from sources under consideration according to scoliosis etiology, n (%)

System	Idiopathic	Systemic	Neurogenic	Congenital	Other
TGR	399 (27.6)	376 (26.0)	363 (25.1)	298 (20.6)	9 (0.6)
VEPTR	129 (15.0)	123 (14.3)	306 (35.6)	299 (34.8)	2 (0.2)
Schilla и Luque Trolley	43 (24.7)	46 (26.4)	68 (39.1)	17 (9.8)	0 (0.0)
Total	571 (23.0)	545 (22.0)	737 (29.7)	614 (24.8)	11 (0.4)

ver in the apical region, and the lack of rigid fixation of the screw heads with longitudinal rods at non-apical anchor points. The indication for its use is scoliosis greater than 50° according to Cobb. A decrease in the number of additional procedures makes the Shilla system a promising alternative to TGR. At current Luque Trolley system [54], rigid screw bases above and below the vertebral curve apex are implanted. These bases are joined by parallel rods, which are then threaded through double screw heads on the deformity's apex. During the growth process, the rods slide along the screws and prevent the deformity from progressing. The indication for the use of the technique is scoliosis greater than 40° according to Cobb in patients with growth potential [55]. The advantage is that there is no necessity for staged surgeries and final (subsequent) procedures for the scoliosis correction.

The Shila and Luque Trolley techniques help to correct deformities well (50 %), while their use is associated with a relatively high complication rate (64 %). Doctors often refuse the final blocking of the instrumentation at the end of treatment (only in 22 % of cases final instrumentation was used).

Alternative growth modulation systems

The VBT technique was first introduced in 2010 [56]. This method allows the use of a flexible cable (cord) attached to the heads of screws implanted into the vertebral bodies along the deformity's convex side. According to a number of authors, indications for its use are described quite selectively: isolated thoracic curves (30–70°) or thoracolumbar or lumbar curves (30–60°) in patients with preserved growth potential. Meanwhile, thoracic hyperkyphosis and lumbar hypolordosis are relative contraindications [57].

During VBS, a C-shaped staple is implanted into adjacent vertebrae along their growth plates from the convex side through the anterior approach, and additional compression is performed. The staples suppress the growth of the spine on the convex side while maintaining spinal mobility. Indications for VBS: idiopathic scoliosis; evaluation of bone maturity according to Risser at 0–2; the Cobb angle of 25–40°; ineffectiveness of spinal bracing treatment [58].

A specific side effect of growth regulation procedures is excessive correction, or more accurately, anti-correction. It occurs when scoliosis is initially corrected as it grows and then develops in the opposite direction. Despite strict indications and limited use, the great advantage of VBT and VBS is the preservation of spinal mobility [59]. It should be noted that we talk about partial mobility in the surgically treated segments. This is due to the fact that initially mobility is limited by torsion. When using VBT, an additional component of rigidity is the tension of the cord when tilted, and with VBS, the position of the staples.

Magnetically Controlled Growing Rods (MCGR)

Magnetically controlled growing rods (MCGR), one of the growing rod variants, were initially shown by Takaso et al. in 1998 [60]. The system contains screws, rods and an external remote control. Between various authors and MCGR connector types, planned distraction frequency and magnitude vary greatly. There is no consistently reliable, approved unified algorithm for this technique [61]. Most surgeons expand the rods once every 3–6 months, which is more often than the mean TGR.

According to the systematic review [7] included 23 papers discussing 504 patients (56 % of girls and 44 % of boys), the mean age of implantation was 8.7 ± 1.9 years, and the follow-up period was 28.0 ± 16.0 months (mean 2 years).

This technique was comparable in efficiency in deformity correction with TGR and Shilla/Luque Trolley, from 68.2° ± 10.8° to 36.6° ± 8.5° (54 % of correction). Nevertheless, the complication rate was about 45 %. Moreover, repeated surgeries were required in 33 % of cases [62].

Undoubtedly, the authors emphasized the advantages of noninvasive distractions on an outpatient basis as more comfortable for patients and their parents [63].

According to a number of comparative economic studies in the American and European healthcare systems, the use of magnetic growing rods is more advantageous in comparison to other technologies during the 4-year treatment period [64–67]. This is due to lower costs for planned admissions to the hospital, procedures, and inpatient days. This difference at the end of treatment compensates and even exceeds the higher cost of the MCGR implant itself compared to the TGR. Nevertheless, a number of other authors indicate that the high number of complications and unscheduled repeated surgeries neutralizes the potential financial benefit from the use of MCGR and makes this treatment option more expensive than TGR.

Alternative growth-friendly systems for the treatment of scoliosis

Posterior Dynamic Deformity Correction (PDDS) [68] combined the mechanisms of two approaches: growth modulation (the spine remains mobile) and noninvasive distraction. The device is mounted on the concave side. It consists of screws at the edges and a rod with a one-way ratchet mechanism. The rod is expanded when the patient performs tilting exercises, and due to the ratchet mechanism, it may not return to the previous length. As a result, the patient himself supports the deformity treatment with the use of exercises.

Researchers from different countries propose various options for fixators to perform distractions either without surgeries at all or by means of minimally invasive approaches. Examples of such systems are the One-Way Self-Expanding Rod [4] and the Self-Adaptive Ratchet Growing Rod [5] that has in common a single principle of using a connector with a ratchet mechanism. The technique promotes the elimination or significant reduction of the invasiveness of planned distractions that is supposed to reduce the number of complications.

One more idea is implemented in the use of spring mechanisms to provide continuous corrective force in the system, for example, the Spring distraction system [6]. A small number of patients and the lack of long-term results, despite promising immediate outcomes, prevent an impartial assessment of their reliability and effectiveness. Moreover, it is essential to remember that the increase in movable elements and the mechanical complications of the instrumentation do not only raise the cost of treatment, but also it unavoidably leads to reduced reliability of the implant and increased risk of various complications.

The hybrid techniques are also worth mentioning. For example, in some cases of congenital scoliosis, when a scoliogenic malformation is combined with concomitant extended scoliosis in an adjacent area, a hybrid technique can be applied. An osteotomy can be done in the area of the defect with simultaneous or staged implantation of the growth-friendly system [69].

The search for a balance between cost, reliability, invasiveness and effectiveness of various treatment techniques is one of the major tasks of modern vertebrology for the treatment of early-onset scoliosis.

Limitations and problematic points of the study

An essential moment is the presence in all articles of X-ray data only at the following control points: before the start of treatment, after the primary surgery, after the end of treatment, and at the time of the last follow-up. Deformity correction indicators at the time of numerous planned distractions, as well as before the final instrumentation, are not described in the articles included in the study. Due to the oddity of the data, a thorough comprehension of how the distraction period developed and an accurate evaluation of the treatment's efficacy are not possible.

Moreover, it is essential to mention that, within the framework of this review, it was possible to assess and compare radiographic findings associated with the spinal deformity correction only. The data concerning changes in the structural and functional parameters of the chest in the reviewed articles appeared to be inadequate for an accurate and objective comparative analysis. There is insufficient information regarding changes in the chest volume (VPI, chest circumference, SAL indices, chest asymmetry index, etc.), which typically affect both the condition of internal organs (lungs and mediastinal organs) and the prognosis for life. There is even less data on changes in lung functional indications (vital lung capacity, respiratory volume, forced expiratory vital capacity, etc.) – only five papers partially contain such information. The correlation between the growth of lung tissue (and, accordingly, the qualitative dynamics of lung function) and the chest volume is most pronounced at the age of up to 8 years, after which this dependence becomes insignificant [70].

One more issue of concern is the recording of complications. Many authors attribute the deformity progression to one of the normal versions of the disease course, not classifying it as a complication at all. Another issue is the assessment of the proximal transitional kyphosis onset that the authors of the examined publications do not always attribute definitively to complications associated with implants or deformity correction. The tremendously uneven and heterogeneous nature of the complications and techniques of their calculation highlighted in the articles is of particular interest. The authors focus differently on the adverse circumstances that have arisen and offer different amounts of data, both in quantitative and qualitative expression.

Conclusion

Treatment techniques for early-onset scoliosis are numerous, while the presented outcomes (mainly data from cohort studies with different criteria and assessment timelines) enable only trends to be estimated. On the one hand, this stipulates the need to collect data for a multifactorial analysis of the results according to the selected criteria and deadlines for assessing the results, and on the other, the incentive of doctors, engineers, and manufacturers to new developments. The treatment always begins with conservative options, and when they are ineffective, surgical correction is used [71]. The best procedure is chosen based on the patient's characteristics and deformity, the surgeon's experience and preferences, as well as the licensed implants accessible in the country.

The literature review on the use of growth-friendly systems in early-onset scoliosis identified a number of trends and problematic points.

1. The use of VEPTR systems is associated with a slightly less effective correction of spinal deformity. Nevertheless, it has considerable advantages in the treatment of thoracic insufficiency syndrome as well as in children of early age. Growth modulation systems (Schilla and Luque Trolley) demonstrate treatment outcomes similar to growing rods, yet also have one of the highest percentages of complications.

2. The following treatment outcomes have not been investigated in the publications: patients' quality of life and functional status, complications, and defor-

mity values at intermediate stages and before final correction, if performed. The majority of the articles do not have information on the age at which the final surgery was performed (rigid system setting or last stage distraction), the condition of the vertebral column outside the fixation zone during and after treatment, or the dynamics of the functional and structural condition of the chest. Most studies focus on the radiographic findings of correction of the main deformity curve, thoracic kyphosis, lumbar lordosis, sagittal balance, and trunk length growth.

3. The number of complications and unplanned scenarios arising during the use of traditional growing rods (TGR) remains quite high. The aim of their modifications is to decrease the number of planned surgeries, the risks of complications, and the comfort of patients in the course of treatment.

A more comprehensive review and evaluation of these factors will promote the revision of conventional treatment guidelines and improve the quality and effectiveness of aid.

The study had no sponsors.
The authors declare that they have no conflict of interest.
The study was approved by the local ethics committee of the institution.
All authors contributed significantly to the research and preparation of the article, read and approved the final version before publication.

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Address correspondence to:
Molotkov Yury Vitalyevich
Russian Ilizarov Scientific Center for Restorative Traumatology and Orthopaedics,
6 M. Ulyanovoy str., Kurgan, 640014, Russia,
m.d.molotkov@gmail.com

Received 02.11.2022
Review completed 27.02.2023
Passed for printing 03.03.2023

Yury Vitalyevich Molotkov, orthopedic surgeon, graduate, Russian Ilizarov Scientific Center for Restorative Traumatology and Orthopaedics, 6 M. Ulyanovoy str., Kurgan, 640014, Russia, ORCID: 0000-0003-3615-2527, m.d.molotkov@gmail.com;

Sergey Olegovich Ryabykh, DMSc, Head of the Department of Traumatology and Orthopedics, Veltishchev Research and Clinical Institute or Pediatrics and Pediatric Surgery of the Pirogov Russian National Research Medical University, 2 Taldomskaya str., Moscow, 125412, Russia; traumatologist-orthopedist, St. Petersburg University's Pirogov Clinic of High Medical Technologies, 154 Fontanka River Embankment, St. Petersburg, 190103, Russia, ORCID: 0000-0002-8293-0521, rso_@mail.ru;

Egor Yuryevich Filatov, MD, PhD, orthopedic surgeon, Russian Ilizarov Scientific Center for Restorative Traumatology and Orthopaedics, 6 M. Ulyanovoy str., Kurgan, 640014, Russia, ORCID: 0000-0002-3390-807X, filatov@ro.ru;

Olga Mikhailovna Sergeenko, MD, PhD, neurosurgeon, orthopedic surgeon, Russian Ilizarov Scientific Center for Restorative Traumatology and Orthopaedics, 6 M. Ulyanovoy str., Kurgan, 640014, Russia, ORCID: 0000-0003-2905-0215, pavlova.neuro@mail.ru;

Ilkhom Eshkulovich Khuzhanazarov, DMSc, Head of the Department of Traumatology, Orthopedics, Military Field Surgery and Neurosurgery, Tashkent Medical Academy, 2 Farabi str., Tashkent, 100109, Uzbekistan; Head of the Department of Orthopedics and Rehabilitation, Republican Specialized Scientific and Practical Medical Center for Traumatology and Orthopedics, 78 Makhtumkuli str., Tashkent, 100047, Uzbekistan, ORCID: 0000-0002-8362-6716, ilkhom707@mail.ru;

Doston Ilkhomovich Eshkulov neurosurgeon, Republican Specialized Scientific and Practical Medical Center of Traumatology and Orthopedics, 78 Makhtumkuli str., Tashkent, 100047, Uzbekistan, ORCID: 0000-0001-7334-1410, dostonjon.eshkulov@mail.ru.