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Original Study Article

Diffusion-tensor magnetic resonance imaging in patients with consequences of obstetric brachial plexus palsy

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ABSTRACT

BACKGROUND: Diffusion-tensor magnetic resonance imaging allows visualizing the conductive pathways of the brain and spinal cord and assessing their structure and integrity and has found wide application in practical medicine. Currently, brachial plexus diffusion-tensor magnetic resonance imaging is not a routine research technique, and very few studies have described its use in children and adolescents.

AIM: This study aimed to evaluate the possibility of brachial plexus diffusion-tensor magnetic resonance imaging application in pediatric patients with obstetric brachial plexus palsy sequelae and identify correlations between the diffusion-tensor magnetic resonance imaging parameters of brachial plexus and parameters of electrophysiological study of the upper extremities in these patients.

MATERIALS AND METHODS: A complex examination of 50 patients was performed. The main group included 30 patients aged 6–17 years, with contractures and secondary deformities of the bones of the shoulder girdle and upper limbs caused by unilateral obstetric brachial plexus palsy. The control group included 20 patients aged 7–17 (10.1 ± 2.1) years without clinical signs, and anamnestic data indicated the presence of damage to the brachial plexus and peripheral nerves of the upper limbs.

RESULTS: No significant differences in diffusion-tensor magnetic resonance imaging parameters of the right and left brachial plexus were found in the control group. Significant differences in fractional anisotropy of the C_5–C_8 tracts on the side of the damaged brachial plexus were detected compared with those on the side of the undamaged brachial plexus. On the side of the injured brachial plexus, nonlinear correlations were found between the fractional anisotropy of the tracts of the spinal nerve and its branches and the amplitude of sensory responses from the sensory nerve, which originated from the anterior branches of this spinal nerve, and between the volume of the branches of the tracts of the spinal nerve and the amplitude of compound motor responses from the muscles, which were innervated by the anterior branches of this spinal nerve.

CONCLUSIONS: Diffusion-tensor magnetic resonance imaging allows for the evaluation of the structural changes in the SNs that participate in the formation of the brachial plexus. The results can be used for further studies of diffusion-tensor magnetic resonance imaging of brachial plexuses in various pathologies in pediatric patients.

Keywords: obstetric brachial plexus palsy; brachial plexus injury; diffusion-tensor magnetic resonance imaging; tractography.

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Оригинальное исследование

Диффузионно-тензорная магнитно-резонансная томография у пациентов с последствиями односторонней родовой травмы плечевых сплетений

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АННОТАЦИЯ

Обоснование. Диффузионно-тензорная магнитно-резонансная томография позволяет визуализировать проводящие пути головного мозга, спинного мозга и оценить их структуру и целостность и находит широкое применение в практической медицине. Диффузионно-тензорная магнитно-резонансная томография плечевых сплетений в настоящее время не является рутинной методикой исследования, а публикации, в которых описано использование диффузионно-тензорной магнитно-резонансной томографии плечевых сплетений у детей и подростков, единичны.

Цель — оценка возможности диффузионно-тензорной магнитно-резонансной томографии плечевых сплетений у пациентов детского возраста с последствиями родовой травмы плечевого сплетения, а также выявление корреляционных связей между параметрами диффузионно-тензорной магнитно-резонансной томографии плечевых сплетений и показателями электрофизиологического исследования верхних конечностей у данных пациентов.

Материалы и методы. Проведено комплексное обследование 50 пациентов. Основная группа: 30 пациентов в возрасте от 6 до 17 (9,8 ± 1,4) лет с контрактурами и вторичными деформациями плечевого сустава вследствие односторонней родовой травмы плечевого сплетения. Контрольная группа: 20 пациентов в возрасте от 7 до 17 (10,1 ± 2,1) лет без клинических признаков и анамнестических данных, указывающих на повреждение плечевого сплетения и периферических нервов верхних конечностей.

Результаты. В контрольной группе не обнаружено статистически значимых различий параметров диффузионно-тензорной магнитно-резонансной томографии правого и левого плечевого сплетения. Определены статистически значимые различия фракционной анизотропии трактов C_5–C_8 на стороне поврежденного плечевого сплетения, по сравнению с этим показателем на стороне неповрежденного плечевого сплетения. На стороне поврежденного плечевого сплетения выявлены нелинейные корреляционные связи между фракционной анизотропией трактов спинномозгового нерва и его ветвей и амплитудой сенсорного ответа от сенсорного нерва, который исходит от ветвей данного спинномозгового нерва, а также между объемом ветвей трактов спинномозгового нерва и амплитудой вызванных моторных ответов от мышц, источником иннервации которых являлись ветви данного спинномозгового нерва.

Заключение. Диффузионно-тензорная магнитно-резонансная томография позволяет оценить структурные изменения спинномозговых нервов, участвующих в формировании плечевого сплетения. Результаты данной работы могут быть использованы для дальнейших исследований диффузионно-тензорной магнитно-резонансной томографии плечевых сплетений при различной патологии у детей.

Ключевые слова: родовая травма плечевого сплетения; повреждение плечевого сплетения; диффузионно-тензорная магнитно-резонансная томография; трактография.

Как цитировать
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BACKGROUND

According to several studies, the occurrence of birth injuries to the brachial plexus ranges from 0.38 to 5.1 per 1,000 neonates [1]. The severity and prognosis of a birth-related neonatal brachial plexus injury do not correlate with its clinical presentation [2]. In 30%–90% of cases, a complete spontaneous recovery of the impaired upper limb functions has been documented [3]. The timing of recovery of upper limb function relies upon the nature of the injury and impacts future treatment and prognosis [3, 4]. One potential mechanism of brachial plexus damage during birth is the long-term (minutes or even hours) low energy stretching of the roots and trunks of the brachial plexus. This can result in a wide range of injuries, including neuropraxia, axonotmesis, and neurotmesis, with partial or complete damage to the trunks of the brachial plexus. In pediatric patients experiencing severe complications from birth injury to the brachial plexus, the development of intratrunk neuromas of damaged nerve trunks is typical. Subsequently, a few axonal fibers intergrow resulting in the emergence of movements in the damaged upper limb at the age of 6–12 months and later [5, 6]. Compared to traction injuries of the brachial plexus in adults, which typically result in avulsion of the spinal nerve roots that form the brachial plexus, the incidence of birth trauma-related spinal nerve root avulsion in pediatric patients is much less common [4].

In pediatric patients with birth-related brachial plexus injuries, complications such as incomplete recovery and dysfunction of the upper limb of varying severity, shortening of the upper limb on the affected side, and limitation in the range of motion in the joints due to multiple muscle contractures and joint deformities are observed. Consequently, the issue is of considerable medical and social importance [7, 8].

An electrophysiological examination is the gold standard for diagnosing brachial plexus injury in patients, as it enables the identification of the extent and type of nerve trunk damage [9]. Furthermore, this technique can be used to determine the exact location of the damage in the case of isolated damage to C_5 and C_6, as well as in the presence of anatomical variability in brachial plexus development and cross innervation [10, 11].

Various imaging techniques, including computed tomography (CT), magnetic resonance imaging (MRI), and ultrasound, are employed to elucidate the diagnosis in the event of a brachial plexus injury. Currently, MRI is the preferred method for visualizing the brachial plexus due to its high specificity for various pathological conditions [12, 13]. Magnetic resonance neurography has become widely used for diagnosing brachial plexus lesions due to its noninvasiveness and ability to analyze the proximal and distal parts of the brachial plexus. Even though MR neurography has replaced CT myelography, which has long been used to detect preganglionic lesions, it cannot be employed to quantify structural alterations [13, 14].

Diffusion tensor MRI (DT MRI) is a promising neuroimaging technology that quantifies water molecule diffusion in various biological tissues. This is facilitated by the mathematical reconstruction of the vectors and diffusion values of water molecules in the studied area and the subsequent graphical display of the predominant trajectory of their movement [15]. This technique also enables quantification of the structural features of peripheral nerve fibers by calculating diffusion parameters, including fractional anisotropy (FA), radial diffusivity (RD), and axial diffusivity (AD). Additionally, it provides insight into the functional state of axons [14]. However, DT MRI of the brachial plexuses is not a routine research technique presently, and related studies describing its findings in children and adolescents are scarce [14, 16].

This study aimed to evaluate the feasibility of using DT MRI in pediatric patients with birth-trauma-related brachial plexus damage and to analyze the reproducibility of DT MRI results, as well as to identify correlations between the parameters of DT MRI of the brachial plexuses and indicators of electrophysiological studies of the upper extremities in patients with consequences of birth injury tothe brachial plexus.

MATERIALS AND METHODS

The study included 30 patients aged 6–17 (9.8 ± 1.4 years) with contractures and secondary deformities of the shoulder joint caused by unilateral birth injury of the brachial plexus. These patients had not undergone microsurgical restoration of the integrity of the damaged brachial plexus trunks. There were 16 boys and 14 girls. Electrophysiological investigation was used to diagnose brachial plexus injuries.

The study's exclusion criteria included bilateral brachial plexus injury, concomitant genetic and systemic diseases, a lack of voluntary informed consent of patients and their representatives to participate in this examination, the need for anesthesia during MRI, and motion artifacts during MRI that impede postprocessing of DT MRI data.

The necessity to ascertain the reference values of DT MRI parameters in pediatric patients was prompted by the absence of data in the Russian and international literature. The control group included 20 patients (12 boys and 8 girls) aged 7–17 years (10.1 ± 2.1 years) with shoulder or elbow joint deformities because of injury. The MRI examination protocol for this group was based on the underlying disease and included an additional MRI sequence to obtain DT MRI data of the cervical spinal cord and proximal brachial plexuses.

The inclusion criteria for the control group were the absence of clinical signs and anamnestic data indicating damage to the brachial plexus due to various etiologies, as well as an age between 7 and 17 years. The exclusion criteria included concomitant genetic and systemic diseases, a lack of voluntary informed consent from the patients and their representatives to participate in this examination, the need for anesthesia, and the presence of motion artifacts during MRI that could impede the postprocessing of DT MRI data.

All patients underwent a comprehensive examination, including a detailed analysis of their medical history, a neurological and orthopedic examination, and a DT MRI of the brachial plexuses. Electrophysiological examinations were conducted exclusively on patients in the main group.

The electrophysiological examination was performed using a four-channel electroneuromyograph, the Neuro-MVP-4 (Neurosoft, Russia). The sensory response parameters elicited during the stimulation of the external cutaneous nerve of the forearm, median, ulnar, and superficial radial nerves on both sides were analyzed. Additionally, the speed of impulse conduction along sensory fibers, the evoked motor responses, and the speed of impulse conduction along motor fibers when stimulating the axillary, musculocutaneous, median, ulnar, and radial nerves on both sides were examined using a standard method [17].

The MRI was performed on a Philips Ingenia Edition X tomograph with a magnetic field strength of 3.0 Tesla (12-channel coil DS-Head–Neck) with the patient in the supine position. Diffusion tensor imaging in the axial plane was incorporated into the study protocol. The sections were oriented perpendicular to the body's midline. The study was conducted over eight minutes and thirty seconds, during which 23 image slices were acquired. The slices had a thickness of 3 mm with no gap between the slices, a matrix of 64 × 62 mm, a voxel size of 2.8 × 2.8 mm, a field of view of 180 × 180 mm, a time of repetition of 4,000 ms, an echo time (TE) of 71 ms, two averages, a diffusion coefficient (b) of 600 s/mm^2, and 15 diffusion directions were employed. The sections were positioned from the midpoint of the C_3 vertebral body to the midpoint of the Th_2 vertebral body, as per the localizer. Postprocessing was performed using the DSI Studio program with built-in statistical analysis methods. Pairwise symmetrical zones of exit of the spinal nerves from the intervertebral foramina were selected as zones of interest (ROI) for the C_5–Th_1 tractograms. Each tractogram was constructed independently. Tracts were constructed with the parameters of a maximum value of FA of 0.18 and a maximum rotation angle of 45°, without restrictions on the minimum length and number of paths, in accordance with the selected area of interest. We implemented standard color coding. To assess reproducibility, threefold construction of brachial plexus tractograms was performed in 15 randomly selected patients in the control group and 30 patients in the main group.

Statistical analysis. The study data was analyzed using the StatTech v.2.8.8 program (developed by StatTech, Russia). The numerical scales were described using the mean and standard deviation in M ± SD format. The two groups were compared on numerical variables using the nonparametric Mann–Whitney test. Comparisons of three or more groups on a quantitative basis were performed using the Kruskal–Wallis test, with an additional post hoc comparison using Dunn's test with Holm correction.

Correlations between the DT MRI and electrophysiological study parameters were assessed using the Spearman's correlation coefficient. The sample was divided into portions where the relationship was monotonic, and correlations were calculated separately for each portion of the sample with a nonlinear correlation relationship. The repeatability of brachial plexus tractography parameters was analyzed using the Cronbach's alpha test.

RESULTS

A total of 160 (100%) tracts of the C_5–C_8 spinal nerves and their branches (SN) and 21 (52.5%) tracts of the Th_1 SN were created for the 20 control group patients. In patients with sequelae related to birth-related unilateral brachial plexus injury, there were 120 (100%) SN tracts C_5–C_8 and 18 (56.7%) SN tracts Th_1 on the side of the intact brachial plexuses, and on the side of the damaged brachial plexuses, 114 (95%) SN tracts C_5–C_8 and 14 (46.7%) SN tracts Th_1 were created.

The repeatability of constructing SN tracts was good (>0.8) in the control group and in the main group on the side

Table 1. Cronbach's alpha coefficient (repeatability of spinal nerve tracts construction)

Roots of spinal nerves and their branches	Group for determining reference values of DT MRI parameters	Patients with sequelae of unilateral birth injury to the brachial plexus	
		on the side of the intact brachial plexus	on the side of the damaged brachial plexus
C_5	0.89	0.9	0.81
C_6	0.87	0.87	0.79
C_7	0.86	0.85	0.76
C_8	0.89	0.87	0.84
Th_1	0.88	0.89	0.85

of the intact brachial plexus, and it was acceptable (>0.7) in the main group on the side of the damaged brachial plexus (Table 1).

The number of SN tracts in the control and main groups remained constant during repeated constructions. We considered the absence of constructed C_5–C_8 tracts to be indicative of avulsion (Fig. 1). The findings were consistent with the electrophysiological examination data.

Since it was not possible to reliably assess the cause of the lack of construction of the Th_1 SN tract (avulsion or technical difficulties in its construction), the data on the Th_1 SN tract parameters were excluded from further analysis.

When analyzing the DT MRI data of the brachial plexuses, there were no statistically significant differences ($p > 0.05$) in the parameters of FA, AD, RD, and MD between the right and left brachial plexuses in the control group (Table 2). The same applied to the data on these indicators on the side of the intact brachial plexus in patients from the main group.

There were no statistically significant gender and age differences ($p > 0.05$) in the above indicators, either in the control group or in patients with the consequences of a unilateral birth injury to the brachial plexus on the side of the intact brachial plexus. This enabled us to perform a comparative analysis of DT MRI parameters on the sides of the damaged and intact brachial plexuses without considering lateralization, age, or gender differences.

There were statistically significant differences ($p < 0.05$) in the FA of the SN tracts C_5–C_8 in the control and main groups (on the side of the damaged brachial plexus) (Fig. 2).

When compared to the control group data, we observed statistically significant differences in the FA of the C_5 SN tracts in 27 (90%) patients in the main group (on the side of the damaged brachial plexus), in 26 (86.6%) cases in the C_6 tracts, in 24 (80%) patients in the C_7 tracts, and in 9 (30%) cases in the C_8 tracts.

There were no statistically significant differences ($p = 0.08$) between AD, RD, and MD of the control and main groups, either on the side of the damaged or intact brachial plexus.

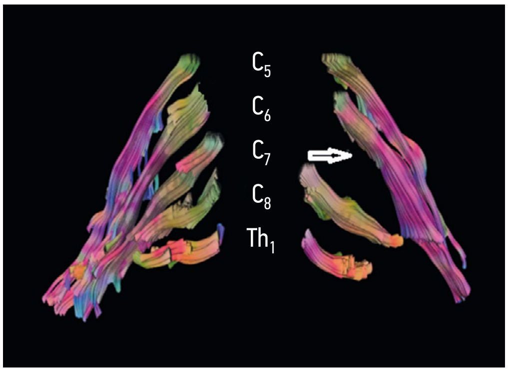

Fig. 1. Patient K., 11 years old. Three-dimensional reconstruction of spinal nerve tracts. Erb's paresis on the left. The absence of SN C_7 is indicated by an arrow

There was no correlation between changes in FA of the SN tracts and the amplitude of motor responses from the muscle innervated by this SN on the side of the injured brachial plexus.

On the side of the damaged brachial plexus, a nonlinear correlation was identified between the FA of the SN tracts and the amplitude of the sensory response from the sensory nerve, which arises from the branches of this spinal nerve. A strong negative correlation ($r = -0.84$) was observed between an increase in the FA of the SN tracts and a decrease in the amplitude of the sensory response from the sensory nerve, which originates from the branches of this spinal nerve on the side of the damaged brachial plexus. We found a moderate positive correlation ($r = 0.54$) between a reduction in FA of SN tracts and a decrease in the sensory response amplitude from the sensory nerve, which originates from the branches of this spinal nerve on the side of the injured brachial plexus.

The DSI STUDIO software package enables statistical analysis, including the determination of the total volume of tracts as well as the individual volumes of trunks and branches of tracts.

In the control group patients, there were no statistically significant differences ($p > 0.05$) in the total volume of the tracts, the volume of branches/trunks of the tracts of the right and left brachial plexus.

The volume of the trunks of the SN tracts decreased on the side of the damaged brachial plexus. However, no

Table 2. Parameters of diffusion tensor MRI of the right and left brachial plexus of patients in the control group and the intact brachial plexus of patients with consequences of birth injury to the brachial plexus (without considering lateralization)

Spinal nerve roots	FA*			MD*			AD*			RD*		
	r	l	n	r	l	n	r	l	n	r	l	n
C_5	0.38 ± 0.012	0.37 ± 0.017	0.37 ± 0.013	1.59 ± 0.17	1.58 ± 0.14	1.6 ± 0.1	2.07 ± 0.09	2.04 ± 0.07	2.09 ± 0.07	1.44 ± 0.15	1.48 ± 0.19	1.49 ± 0.17
C_6	0.37 ± 0.017	0.36 ± 0.02	0.36 ± 0.017	1.61 ± 0.13	1.57 ± 0.15	1.59 ± 0.07	2.05 ± 0.13	2.11 ± 0.06	2.11 ± 0.12	1.61 ± 0.11	1.52 ± 0.17	1.58 ± 0.13
C_7	0.37 ± 0.016	0.37 ± 0.018	0.36 ± 0.011	1.62 ± 0.08	1.59 ± 0.12	1.61 ± 0.15	2.12 ± 0.06	2.09 ± 0.13	2.09 ± 0.13	1.54 ± 0.09	1.59 ± 0.01	1.5 ± 0.17
C_8	0.35 ± 0.016	0.36 ± 0.014	0.36 ± 0.09	1.58 ± 0.13	1.6 ± 0.17	1.62 ± 0.11	2.07 ± 0.11	2.09 ± 0.08	2.05 ± 0.01	1.59 ± 0.17	1.56 ± 0.12	1.52 ± 0.18

Note: r — right brachial plexus in patients from the control group; l — left brachial plexus in patients from the control group; n — intact brachial plexus of patients with consequences of birth injury of the brachial plexus; * no statistically significant differences $p > 0.05$.

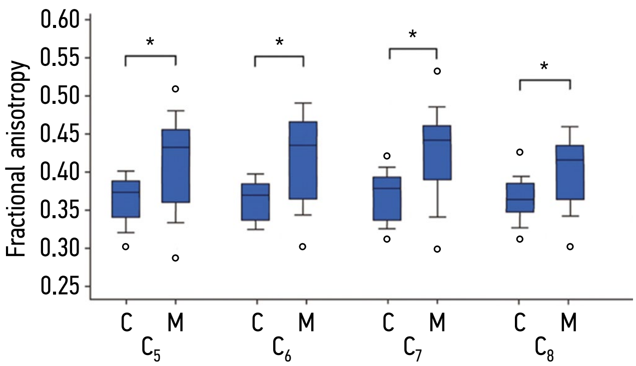

Fig. 2. Fractional anisotropy of the C_5–Th_1 spinal nerve tracts. C — control group; M — main group (on the side of the damaged brachial plexus); * statistically significant differences ($p < 0.05$)

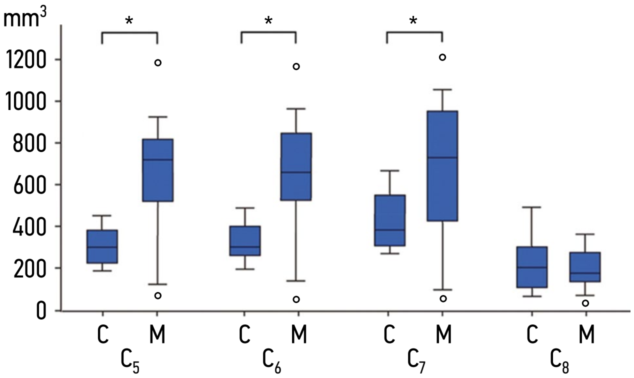

Fig. 3. The volume of branches of the spinal nerve tracts on the sides of the damaged (M) and intact brachial plexus (C). * Presence of statistically significant differences between the volume of branches of the SN tracts of the damaged and intact brachial plexus

statistically significant differences in the volume of the trunks of the tracts on the side of the damaged and intact brachial plexus were registered ($p = 0.09$).

In contrast to the intact side, the volume of the branches of the SN tract C_5–C_7 on the side of the damaged brachial plexus exhibited statistically significant differences ($p < 0.05$). There were no statistically significant differences in the volume of C_8 tract branches (Fig. 3).

The total volume of the SN tracts may have decreased on the side of the damaged brachial plexus compared to the intact brachial plexus (Fig. 4) due to a decrease in the volumes of both branches and trunks of the tracts.

Compared to the intact brachial plexus, the total volume of the SN tracts could be increased on the damaged side owing to an increase in the volume of the tract branches (Fig. 5).

A nonlinear correlation was observed between the volume of branches of the SN tracts and the amplitude of evoked motor responses from the muscles that were innervated by the branches of the SN on the side of the damaged brachial plexus. A moderate positive correlation ($r = 0.41$) was identified between a decrease in the volume of the branches of the SN tracts and a decrease in the amplitude of evoked motor responses from the muscles that were innervated by the branches of this SN. A strongly positive correlation ($r = 0.84$) was noted between an increased volume of the SN tract branches and the amplitude of the evoked motor response of the muscles that were innervated by the branches of the SN.

DISCUSSION

Biological barriers (membranes) or an increase or decrease in extracellular space may restrict the diffusion of water in body tissues to a greater or lesser extent [14]. The epineurium, perineurium, and endoneurium are among the several barriers to water diffusion found in peripheral nerves. Peripheral nerves are imaged using the same methodology as white matter tracts in the central nervous system [18, 19]. Using tracking algorithms based on calculated diffusion tensors, DT MRI of the brachial plexus enables the three-dimensional visualization of the spinal nerves involved in brachial plexus formation, providing insight into the continuity of the extraforaminal nerve structures that form the brachial plexus [16].

Our assessment of the reproducibility of tract construction (intrarater interaction) is comparable to data from other studies [20, 21], however, it is inferior to them due to the lack of research on interrater interaction.

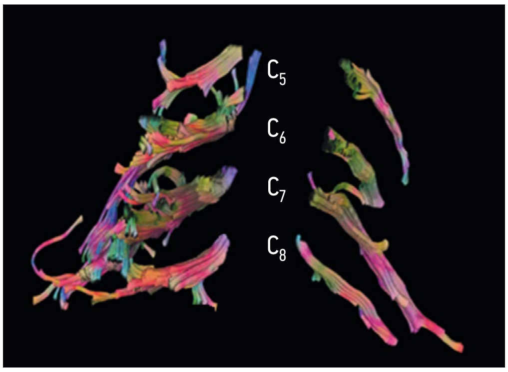

Fig. 4. Patient V., 15 years old. Three-dimensional reconstruction of SN tracts C_5–C_8. Damage to the left brachial plexus. Decreased volume of C_5–C_8 tract branches and trunks. SN Th_1 is not constructed

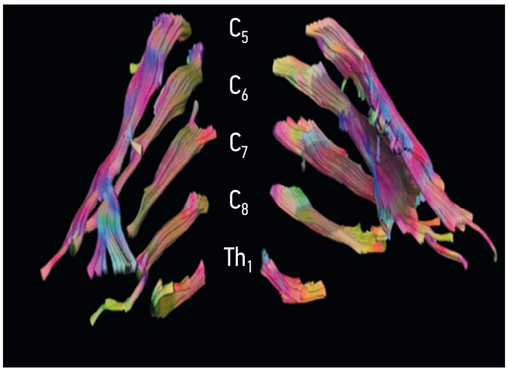

Fig. 5. Patient M., 7 years old. Three-dimensional reconstruction of brachial plexus tracts. Erb's paresis on the left. Increased volume of branches of the SN tracts C_5–C_7

The construction of Th_1 SN tracts was challenging due to various factors that have been described in the literature, including their proximity to the first rib, apex of the lung, subclavian vessels, and respiratory movements during scanning, which could cause an incorrect depiction of this SN [16, 21, 22].

The modern medical literature does not contain any information regarding the significance of FA, AD, and RD indicators in children and adolescents. However, it is reported that there are no differences in these indicators between the right and left brachial plexus in adults [20, 21, 23]. According to A. Tagliafico et al. the utilization of DT MRI parameters of the intact limb in the evaluation of monolateral brachial plexus pathology, such as unilateral birth injury of the brachial plexus, is permissible due to the absence of statistically significant differences in the parameters of DT MRI of the right and left upper limbs [20].

The absence of gender differences in FA, MD, AD, and RD in the control group is consistent with the findings of other authors who have examined these brachial plexus [22, 24], lumbosacral plexus [25], and peripheral nerves [26] DT MRI parameters in adults without neurological pathology.

We were unable to locate any data on age-related differences in DT MRI parameters of the brachial plexuses in pediatric patients in the literature. X. Su et al. conducted a study of 55 volunteers with an average age of 40.53 ± 13.5 years and found a weak negative correlation ($r = -0.25$, $p = 0.011$) between age and the FA value of the C_8 tracts. However, no Th_1 correlations were found between these parameters for the C_5–C_7 tracts [23]. According to K. Tanitame et al., the peripheral nerve FA varies with age. In a study of tibial nerve FA in 26 healthy subjects aged from 23 to 69 years, the authors observed that tibial nerve FA remains unaltered until 45 years of age, and a statistically significant decrease in this indicator is observed after 45 years of age [27].

We did not consider the influence of body mass index in our study, as the control and main groups that were examined included children of predominantly normosthenic build without signs of obesity.

The control group's FA values for the SN tracts C_5–C_8 matched the FA data of a meta-analysis of DT MRI normative values conducted by R.G. Wade et al. [28]. However, the FA of the C_5–C_8 SN tracts in the control group was marginally lower than the FA values reported in the data compiled by A. Tagliafico et al. [20] and M.J. Ho et al. [21]. These differences in FA may be due to the technical characteristics of MRI machines and scanning techniques [29, 30], which differ in the method of selecting the "zone of interest" and the use of different postprocessing methods [28, 31].

Since DT MRI parameters are typically sensitive to several tissue characteristics (e.g., myelination, axon diameter, fiber density, and fiber organization), the reliable relationship between diffusion MR markers of peripheral nerves and their structural changes is still a matter of debate [15].

The observed alteration in FA value may be interpreted in several ways [32]. It has been documented that a decrease in peripheral nerve FA is noted in patients with inflammatory and compressive neuropathies due to various etiologies [33–35]. In patients who have sustained peripheral nerve injuries, FA levels decrease; however, this parameter is nearly restored to its initial levels over time following microsurgical nerve integrity restoration [36].The patients with birth trauma sequelae included in this study had not undergone any microsurgical restoration of nerve integrity. A decrease in FA of the SN tracts on the side of the damaged brachial plexus may serve as a marker of incomplete SN recovery.

The study findings suggest that the proliferation of connective tissue against intrastem neuroma increases SN density on the side of the damaged brachial plexus increasing FA. Liang Chen et al. conducted a histological study of intrastem neuroma in 28 patients with consequences of birth injury of the brachial plexus. The study revealed a significant proliferation of epi- and perineurium, and the average rate of regenerating nerve fibers in the neuroma was 41.83% (38.69–44.69%) [37]. It is necessary to consider that the statistical software DSI STUDIO calculates the average value of FA for the entire tract. The data acquired do not contradict the results of previous studies, which suggests that the decrease in FA may is due to the insufficient restoration of peripheral nerves [36, 38].

The absence of statistically significant changes in AD between the main group on the side of the damaged brachial plexus and the control group is attributable to the duration of the injury. The AD diminishes within two weeks of injury, as per I.V. Manzanera Esteve et al. [39]. RD is a biomarker of myelin sheath integrity [40]. The absence of statistically significant changes in RD between the main group on the side of the damaged brachial plexus and the control group is due to the fact that the speed of impulse conduction along the nerve fibers is restored in the long-term period in birth trauma-related brachial plexus injury, [41] and, therefore, the integrity of the myelin sheath is not significantly impaired.

M. Payen et al. were the sole authors to analyze the volume of the SN tracts that comprise the brachial plexus. They, like the authors of this study, did not observe statistically significant differences in the tract volumes of the right and left brachial plexus in healthy volunteers. The largest volume of tracts was recorded in SN C7, as per M. Payen et al. and our study [42].

The study results indicated that the volume of the branches of the tracts of the SN, which were the source of innervation for the muscle on the side of the damaged brachial plexus, was positively correlated with the amplitude of the evoked motor response. This is explained by the regeneration characteristics of damaged nerves. With partial injury to nerves at any level, restoration occurs due to the remaining axons, and the latter begin to grow and branch actively, producing numerous fibers that penetrate denervated muscle fibers or skin areas. This phenomenon is the basis for compensatory-restorative reinnervation [43]. However, compared with the distal peripheral nerves, the trunks of the brachial plexus give rise to a substantially greater number of branches than the distal peripheral nerve. Therefore, in our opinion, the evaluation of the volume of the branches of the SN tracts more accurately reflects SN function restoration than the FA value of the SN tracts.

Experimental and clinical studies on the regeneration of sensory fibers reveal that they exhibit slower recovery compared to motor ones, especially under conditions of severe SN damage [41, 44, 45]. In the late recovery period, evaluating the amplitude of the sensory response is a more sensitive method for assessing the severity of axonal damage in patients with sequelae of birth injury to the brachial plexus than analyzing the amplitude of the motor response [41, 46].

A strong negative correlation between an increase in FA tracts of the SN and a decrease in the amplitude of the sensory response from the sensory nerve, which branches out of the SN on the side of the damaged brachial plexus, is likely indicative of significant damage to the SN, against which the formation of neuroma and/or fibrous-scarring changes was observed, which caused an increase in FA.

A moderate correlation between the decrease in the amplitude of the sensory response from the sensory nerve, which branches out of the SN on the side of the damaged brachial plexus, and a decrease in the FA tracts of the SN apparently indicates its incomplete recovery.

Our study had several limitations. First, the number of patients included in the study was small. However, to identify potential age and gender-based disparities, we assessed not only the DT MRI data of the intact brachial plexus but also the DT MRI parameters of children and adolescents who lacked clinical signs and anamnestic data indicating damage to the brachial plexus due to various etiologies. Second, we did not conduct correlations with other imaging modalities, such as brachial plexus ultrasound. Third, we did not analyze inter-rater consistency because DT MRI is not a routine technique and there are no publications on DT MRI of the brachial plexuses in the Russian scientific literature.

CONCLUSION

DT MRI of the brachial plexus is reproducible both for healthy children and adolescents and in patients who have experienced the consequences of birth injury to the brachial plexus. For the first time, correlations between electrophysiological study parameters and DT MRI in pediatric patients with consequences of birth injury to the brachial plexus in the late recovery period are presented. This indicates the potential to evaluate structural changes in the SN that constitute the brachial plexus. The results of this study may be applied to additional studies of DT MRI of the brachial plexuses for various pathologies in pediatric patients. However, they should be interpreted with caution since DT MRI is based on mathematical models and does not exclude the possibility of erroneous interpretation of the data obtained. Additional research is required to explore the feasibility of introducing DT MRI into routine clinical practice, which includes the evaluation of neonates with brachial plexus birth injuries using DT MRI.

ADDITIONAL INFORMATION

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Consent for publication. The patients' legal representatives gave voluntary consent to participate in the study and publish the data.

Author contributions. All authors made significant contributions to the study and preparation of the article, and read and approved the final version before its publication.

The author contribution are as follows: *A.M. Khodorovskaya* created the study design, wrote the text of the article, analyzed the literary sources, performed reconstruction (postprocessing) of diffusion tensor MRI data; *A.Yu. Efimtsev* performed final editing of the article text; *O.E. Agranovich* created the study design, edited the text of the article; *M.V. Savina, V.V. Morozova* performed analysis and description of neurophysiological examinations, search and analysis of literary sources; *V.I. Zorin, D.B. Vcherashniy* performed staged editing of the article text; *A.S. Lukyanov, A.I. Arakelian, A.S. Grishchenkov, Ya.A. Filin* performed search and analysis of literary sources; *S.A. Braylov* performed analysis and description of radiation studies, search and analysis of literature.

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