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Variant anatomy and codes of the human brachial plexus

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Abstract

Background. Understanding the complexities of formation and structural features of the brachial plexus remains important for diagnosis, effective surgical treatment and regional anesthesia.
Aim. To identify variants of the brachial plexus structure and develop a system for their coding.
Material and methods. Macroscopic anatomical layer-by-layer and macro-microscopic intratubular dissection of 121 brachial plexus preparations were performed in 105 cadavers of men and women aged 40–100 years. A database was formed from the obtained indicators in the MS Excel 2012 program, and their processing was carried out using Statistica for Windows 12. All indicators were tested for the normal distribution using the Shapiro–Wilco criterion. When describing the studied indicators, the median (Me) and interquartile intervals [Q_1, Q_3] were determined, as well as the significance of intergroup differences according to the Mann–Whitney test.
Results. It was established that the farther from the spinal cord, the more variants of the macroscopic and macro-microscopic structure of the brachial plexus elements exist: roots — 3, trunks — 7, divisions — 3, bundles — 12–16, and a total of 20 variants of the general structure were identified. The roots of spinal nerves C_6 (66.1%), C_7 (66.4%) and C_8 (64.2%) take the greatest part in the formation of brachial plexus bundles, 2 times less often — C_5 (34.8%) and Th_1 (33.3%), very rarely — C_4 (2.5%) and Th_2 (0.8%). Reverse coding of variants of the brachial plexus structure in the direction: bundle ← division ← trunk (root) allows to briefly and clearly display the entire morphological diversity of the nervous system of the human upper limb. The results obtained should be taken into account when diagnosing injuries, performing regional anesthesia, reconstructive operations, rehabilitation measures, creating neurosimulators, neurochips, and nerve conductors.
Conclusion. 20 different variants of the general structure of the human brachial plexus have been identified and a reverse coding system has been developed.
Keywords: variants, brachial plexus, roots, trunks, divisions, bundles, codes.

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Background

The brachial plexus is a network of nerve fibers located in the neck and axillary fossa that provides sensory, motor, and autonomic innervation of the upper limb [1, 2]. Brachial plexus injuries account for 20%–28% of peripheral nerve injuries and can cause long-term disability during the most active age [3–5]. Further study of the variant anatomy of this section of the nervous system is of great scientific, medical, and social importance [6, 7] for these reasons.

Several researchers have extensively studied the unique characteristics of the brachial plexus structure [8–10]. They identified various rare anatomical variations in this structure along the entire length of the brachial plexus. At the root level, in addition to the primary structure, they have described prefixal or postfixal variants of brachial plexus formation [11–15]. At the trunk level, typically one to four variants are identified [16, 17]. At the bundle level, there are usually one to three variants [18, 19]. However, at the peripheral nerve level, the number of variants increases considerably [20, 21].

To date, most studies have only detailed the variants of the brachial plexus structure at the macroscopic level [22]. Simultaneously studying the variants of all brachial plexus elements at the macroscopic and macromicroscopic levels has been insufficiently conducted. The absence of this information prevents a complete and holistic understanding of each brachial plexus variant [23–25].

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Currently, no unified methodology is available for anatomical studies, and no coding system has been developed for variants. This lack of standardization prevents a clear, accurate, and complete reflection of the diversity of the external and internal brachial plexus structures [26]. Filling this gap will improve the understanding of clinical manifestations and the level of damage to all brachial plexus elements and preserve their integrity during surgery and regional anesthesia [27–29].

Aim

This study aimed to identify variants in the brachial plexus structure and to suggest a coding system for these variants.

Materials and methods

The study was conducted in the Cadaver Examination Department of the Krasnoyarsk Regional Forensic Medical Examination Bureau on 121 brachial plexus preparations from 105 male and female corpses aged 40–100 years. The brachial plexus was studied from the right side in all cadavers and was studied from both sides simultaneously in 16 cadavers. The choice of the right side was predominant and was associated with a higher frequency of right brachial plexus injuries.

The cadavers were stored in a cold room at +3°C before the study. The duration between death and dissection was up to 20 h. The cause of death in all cases was general somatic diseases without injuries to the upper limbs, thorax, neck, or head. The anatomical study received approval from the Ethical Committee of Prof. V.F. Voyno-Yasenetsky Krasnoyarsk State Medical University (protocol No. 91 dated September 11, 2018).

This study analyzed the variants in the brachial plexus structure through macroscopic layer-by-layer and macromicroscopic intramural dissections. The first stage involved layer-by-layer anatomical dissection, isolating all brachial plexus elements, including roots, trunks, divisions, bundles, and peripheral nerves. The study measured the length, thickness, and angles of inclination and assessed the location of all brachial plexus elements relative to each other and the clavicle.

During the second stage, we used an MBS-10 stereoscopic loupe to perform an intraventricular macromicroscopic dissection, isolating seven nerve fibers of the roots (C_4, C_5, C_6, C_7, C_8, Th_1, and Th_2) along the entire length of the brachial plexus to the peripheral nerves. Special attention was paid to the sources of formation of trunks, divisions, bundles, and the entire brachial plexus.

A database was created using the indicators obtained in the MS Excel 12.0 program, and the results were analyzed using Statistica for Windows 12.0. The statistical analysis began by checking the normality of the distribution of the indicators using the one-sample Shapiro–Wilk criterion. Because the indices of the length of brachial plexus bundle formation did not follow a normal distribution, the central tendencies and dispersions were assessed by determining the median (Me) and quartiles [Q_1; Q_3]. This study determined the absolute and relative occurrence (% of 121 preparations) of variants in the brachial plexus structure.

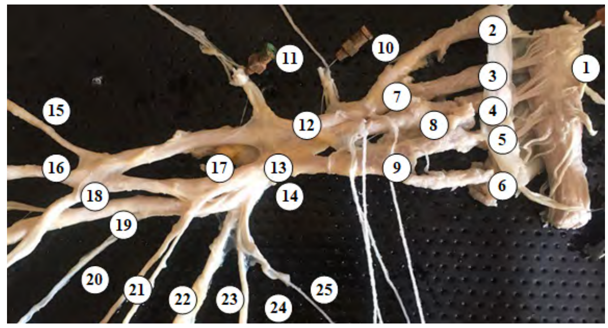

Fig. 1. Macropreparation of the right brachial plexus of a 78-year-old woman's cadaver: 1, spinal cord; 2, C5 root; 3, C6; 4, C7; 5, C8; 6, Th1; 7, upper trunk; 8, middle trunk; 9, lower trunk; 10, supraspinous nerve; 11, lateral thoracic nerve; 12, lateral bundle; 13, medial bundle; 14, posterior bundle; 15, musculocutaneous nerve; 16, median nerve; 17, medial thoracic nerve; 18, ulnar nerve; 19, radial nerve; 20, inferior subclavian nerve; 21, medial cutaneous nerve of the forearm; 22, medial cutaneous nerve of the upper arm; 23, axillary nerve; 24, sternospinal nerve; and 25, superior subclavian nerve.

Results

The human brachial plexus comprises roots, trunks, divisions, bundles, and short and long peripheral nerves (Fig. 1).

Macroscopic layer-by-layer dissection revealed substantial variability in the structure of the brachial plexus throughout its entire length. In 89.1% of cases (106 out of 121 plexuses), the human brachial plexus is classically formed, comprising four lower cervical roots and one upper thoracic root (C_5, C_6, C_7, C_8, and Th_1; see Fig. 2A). In 8.4% of cases (10 out of 121 plexuses), the brachial plexus is formed by the fourth cervical root (C_4, C_5, C_6, C_7, C_8, and Th_1; Fig. 2B), and in 2.5% (3 out of 121 plexuses), the second thoracic root (C_5, C_6, C_7, C_8, Th_1, and Th_2) also participates. By thickness, the roots are arranged in the following sequence: C_7>C_6, C_8>Th_1>Th_2>C_5>C_4; by length: C_6>C_7>C_8>C_5>Th_1>C_4>Th_2.

When the nerve fibers of 5–7 roots intertwine, seven variants of the brachial plexus trunk structure are formed:

– The most common type of structure is the classical type, which accounts for 84.1% (100 plexuses)

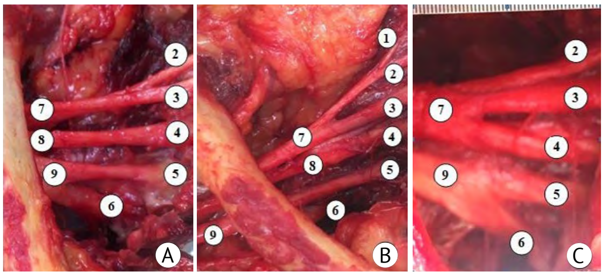

Fig. 2. Formation of the trunks of the right brachial plexus in three cadavers: a 68-year-old man (A), a 71-year-old man (B), and an 85-year-old woman (C): 1, spinal nerve C4; 2, C5; 3, C6; 4, C7; 5, C8; 6, Th1; 7, upper trunk, 8, middle trunk, and 9, lower trunk.

of cases. In this type, the upper trunk is formed by roots C_5 and C_6, the middle trunk by root C_7, and the lower trunk by roots C_8 and Th_1 (Fig. 2A).

The second variant occurs in 7.6% of cases (nine plexuses). The upper trunk is formed by roots C_4, C_5, and C_6, the middle trunk by root C_7, and the lower trunk by roots C_8 and Th_1 (Fig. 2B).

– The upper trunk of the third variant (2.5%, three plexuses) is formed by roots C_5 and C_6; the middle trunk, by root C_7; and the lower trunk, by roots C_8, Th_1, and Th_2;

– The upper trunk of the fourth variant (2.5%, three plexuses) is formed by roots C_5, C_6, and C_7, whereas the lower trunk is formed by roots C_8 and Th_1 (Fig. 2B).

– The upper trunk of the fifth variant (1.7%, two plexuses) is formed by roots C_5 and C_6; the lower trunk, by roots C_7, C_8, and Th_1.

– The upper trunk of the sixth variant (0.8%, one plexus) is formed by roots C_4 and C_5; the middle trunk, by roots C_6 and C_7; and the lower trunk, by roots C_8 and Th_1.

– The upper trunk of the seventh variant (0.8%, one plexus) is formed by root C_5; the middle trunk, by roots C_6 and C_7; and the lower trunk, by roots C_8 and Th_1.

Consequently, in 4.2% of cases (five plexuses), the middle trunk of the brachial plexus is absent.

The trunks split distally over a length of 5.9 [4.5; 6.6] cm into anterior and posterior divisions, which form brachial plexus bundles unequally relative to the clavicle. In 24.5% of cases (25 plexuses), trunk divisions form 0.8 [0.5; 1.0] cm above the clavicle. Most commonly, 57.9% of cases (59 plexuses) form behind the clavicle for 1.8 [1.6; 2.0] cm, and 17.6% of cases (18 plexuses) form along the inferior edge of the clavicle.

Brachial plexus divisions in humans contribute to the formation of fascicles to varying degrees. Four structural variants were identified in the formation of the lateral bundle: In 89.2% of cases (108 plexuses), the anterior divisions of the upper and middle trunks participate; in 5.8% of cases (seven plexuses), all three divisions (upper, middle, and lower) participate; in 3.3% (four plexuses), only one upper trunk participates; and in 1.7% (two plexuses), two trunks participate (upper and lower). Consequently, the anterior division of the upper trunk participates in lateral fascicle formation in all cases, the middle trunk is involved in 95% of cases, and the lower trunk in only 7.5%.

Two variants of medial bundle formation were observed in this study. In 94.2% (114 plexuses), the anterior division of only one lower trunk was involved, whereas in the remaining 5.8% of cases (seven plexuses), the middle and lower trunks were involved. Therefore, the upper trunk does not contribute to forming the medial bundle of the brachial plexus. In addition, the middle and lower trunks have an anterior division in 5.8% and 100% of cases, respectively.

Posterior bundle formation exhibited four structural variants. In 82.6% of cases (100 plexuses), the posterior divisions of the upper, middle, and lower trunks were involved. In 9.9% (12 plexuses), only the upper and middle trunks were involved. In 4.2% (five plexuses), the upper and lower trunks were involved, and in 3.3% (four plexuses), only the middle and lower trunks were involved. Consequently, the posterior divisions of the upper, middle, and lower trunks participate in forming the posterior bundle in 96.7%, 95.8%, and 90.1% of cases, respectively.

The average frequency of trunk divisions participating in the formation of all bundles is as follows:

Upper trunk: (100% + 0 + 96.7%)/3 = 65.6%;

Middle trunk: (95% + 5.8% + 95.8%)/3 = 65.5%;

Lower trunk: (7.5% + 100% + 90.1%)/3 = 65.9%.

Consequently, trunks are equally often involved in forming brachial plexus bundles.

Macromicroscopic intramural dissection revealed the variable formation of brachial plexus bundles by nerve fibers of the roots. The lateral bundle of the brachial plexus can be formed by the nerve fibers of 3–5 roots in four different variants, with a prevalence of 85%. Nerve fibers form 7% of the plexuses (102) from three roots (C_5, C_6, and C_7), 7.6% (nine plexuses) from four roots (C_4, C_5, C_6, and C_7), 5.9% (seven plexuses) from four roots (C_5, C_6, C_7, and C_8), and 0.8% (one plexus) from three roots (C_4, C_5, and C_6). Nerve fibers from roots C_4, C_5, C_6, C_7, and occasionally C_8 form the lateral bundle, whereas roots Th_1 and Th_2 are uninvolved. These percentages are based on the frequency of nerve fiber participation: C_4 (7.6%), C_5 (99.2%), C_6 (100%), C_7 (99.2%), and C_8 (5.9%).

The medial bundle of the brachial plexus is formed by nerve fibers of 2–4 roots, depending on the variant. In 91.6% (109 plexuses), it is formed by nerve fibers of two roots (C_8 and Th_1). In 5.9% (7 plexuses), it is formed by nerve fibers of three roots (C_7, C_8, and Th_1), and in 2.5% (3 plexuses), it is formed by nerve fibers of three roots (C_8, Th_1, and Th_2). Therefore, nerve fibers from roots C_4, C_5, C_6, and C_7 do not contribute to forming the medial bundle. The C_8 root participated in 100% of cases, the Th_1 root in 100%, and the Th_2 root in 2.5% of cases.

The posterior bundle is formed by nerve fibers of 2–4 roots. There are 5 variants: In 83.2% (99 plexuses), it is formed by nerve fibers of three roots (C_6, C_7, and C_8); in 10% (12 plexuses), it is formed by two roots (C_6 and C_7); in 3.4% (4 plexuses), it is formed again by three roots (C_5, C_6, and C_7); in 1.7% (2 plexuses), it is formed by four roots (C_5, C_6, C_7, and C_8); and in 1.7% (2 plexuses), it is formed by two roots (C_7 and C_8). In the formation of the posterior bundle, fibers of the C_5 root participate in 5.1% of cases, whereas C_6 fibers participate in 98.3%, C_7 fibers in 100%, and C_8 fibers in 86.6%. Nerve fibers from C_4, Th_1, and Th_2 roots do not participate.

The average frequency of participation of the nerve fibers of the seven roots in the formation of all three bundles is as follows:

– C_4: (7.6% + 0 + 0)/3 = 2.5%;
– C_5: (99.2% + 0 + 5.1%)/3 = 34.8%;
– C_6: (100% + 0 + 98.3%)/3 = 66.1%;
– C_7: (99.2% + 0 + 100%)/3 = 66.4%;
– C_8: (5.9% + 100% + 86.6%)/3 = 64.2%;
– Th_1: (0 + 100% + 0)/3 = 33.3%;
– Th_2: (0 + 2.5% + 0)/3 = 0.8%.

According to the frequency of participation in the formation of brachial plexus bundles, the nerve fibers of the roots are distributed in the following order: $C_7 > C_6 > C_8 > C_5 > Th_1 > C_4 > Th_2$.

Macroscopic and macromicroscopic dissections of 121 human cadavers revealed variations in the structure of brachial plexus roots, trunks, divisions, and bundles. The data obtained in humans identified 20 variants of the general structure of the brachial plexus, which are presented in Table 1. To visualize the structure of all brachial plexus elements and facilitate subsequent lifetime diagnostics, a reverse coding system of variants toward bundle ← division ← trunk (root) was proposed.

With the data obtained on the structural variants and accurately diagnosed damage to the brachial plexus elements, an individual approach can be taken when performing regional anesthesia, reconstructive surgeries, and rehabilitation measures and creating neurotrainers, neurochips, and nerve guides.

Discussion

Understanding the complexities of brachial plexus formation and structure is crucial for diagnosis, effective surgical treatment, and regional anesthesia [2, 21]. The structure of the brachial plexus in humans is highly diverse and has been extensively studied [7–10]. The literature reports 38 variants, and in fetuses, variations in brachial plexus structure are even more common, occurring in every other person [11, 27, 29].

Our dissection of 121 brachial plexus preparations revealed an uneven number of variants in the structure of all brachial plexus elements, including roots, trunks, divisions, and bundles. Three variants of brachial plexus formation were noted by all researchers but with varying frequencies. According to our data, the classical variant of brachial plexus formation involves the roots of C_5, C_6, C_7, C_8, and Th_1 in 89.1% of cases. Involvement of C_4 is noted in 8.4% of cases, whereas Th_1 is involved in 2.5%. The frequency of these variants varies considerably according to the authors: 68%–97%, 9.4%–65%, and 2%–15%, respectively [1, 2, 14, 18, 26]. In brachial plexus formation, roots C_4 and Th_2 very rarely (0.1%) participate simultaneously. Our studies did not encounter this variant.

Variations in the brachial plexus can result in differences in innervation, leading to confusing symptomatology in root impingement and difficulties in diagnosis [1]. Surgeons performing surgery for spasmodic torticollis and breast cancer must ensure that roots C_4 and Th_2 are isolated from the brachial plexus to prevent injury and impaired innervation of the back and upper extremities. In addition, if Th_2 contributes to lower trunk development, this root may become compressed by the first rib, resulting in neurovascular symptoms [26].

According to our data, the classical variant of upper (C_5 and C_6), middle (C_7), and lower (C_8 and Th_1) trunk formation occurs in 84.2% of cases, whereas the remaining six variants account for 15.8%. Some investigators have also identified rare variants of the classic variant in 15%–36% of cases [30–32]. Additionally, there are reports (22.2%) of a fourth trunk in the brachial plexus [28, 33]. Our data did not yield any such results. However, we found two rare variants of middle trunk absence in 4.2% of cases and lower trunk absence in 1.7%. In the literature, the former variant is described in only one cadaver, that of a 52-year-old Indian male [16]. We also found that in 25% of cases, the middle and lower trunks were fused into one common trunk [34]. In fetuses, the lower and upper trunks are absent in 9% and 1% of cases, respectively [11].

The absence of a trunk increases the likelihood of nerve root detachment when the brachial plexus is stretched downward [1, 3, 4]. A combination of five roots and three trunks can withstand more stress than an isolated arrangement of spinal nerves.

Table 1. Codes of brachial plexus structure variants in human cadavers (n = 121)

No.	**Bundle** ← division ← trunk (root)	Incidence, %
1	**LB**←AD←UT(C_5,C_6), AD←MT(C_7); **MB**←AD←LT(C_8,Th_1); **PB**←PD←UP(C_6), PD-MT(C_7), PD←LT(C_8)	79–65.3
2	**LB**←AD←UT(C_5,C_6), AD←MT(C_7); **MB**←AD←LT(C_8,Th_1); **PB**←PD←UT(C_6), PD←MT(C_7)	7–5.8
3	**LB**←AD←UT(C_4,C_5,C_6), AD←MT(C_7); **MB**←AD←LT(C_8,Th_1); **PB**←PD←UT(C_6), PD←MT(C_7), PD←LT(C_8)	6–5.0
4	**LB**←AD←UT(C_5,C_6), AD←MT(C_7); **MB**←AD←MT(C_7), AD←LT(C_8,Th_1); **PB**←PD←UT(C_6), PD←MT(C_7), PD←LT(C_8)	4–3.3
5	**LB**←AD←UT(C_5,C_6), AD←MT(C_7); **MB**←AD←LT(C_8,Th_1); **PB**←PD←UT(C_5, C_6), PD←MT(C_7)	3–2.5
6	**LB**←AD←UT(C_5,C_6), AD←MT(C_7); **MB**←AD←LT(C_8,Th_1,Th_2); **PB**←PD←UT(C_6), PD←MT(C_7), PD←LT(C_8)	3–2.5
7	**LB**←AD←UT(C_5,C_6,C_7); **MB**←AD←LT(C_8,Th_1); **PB**←PD←UT(C_6,C_7), PD←LT(C_8)	3–2.5
8	**LB**←AD←UT(C_4,C_5,C_6), AD←MT(C_7); **MB**←AD←LT(C_8,Th_1); **PB**←PD←UT(C_6), PD←MT(C_7)	2–1.7
9	**LB**←AD←UT(C_5,C_6), AD←MT(C_7), AD←LT(C_8); **MB**←AD←LT(C_8,Th_1); **PB**←PD←UT(C_6), PD←MT(C_7)	2–1.7
10	**LB**←AD←UT(C_5,C_6), AD←MT(C_7), AD←LT(C_8); **MB**←AD←LT(C_8,Th_1) **PB**←PD←UT(C_6), PD←MT(C_7), PD←LT(C_8)	2–1.7
11	**LB**←AD←UT(C_4,C_5), AD←MT(C_6,C_7); **MB**←AD←MT(C_7), AD←LT(C_8,Th_1); **PB**←PD←MT(C_6, C_7), PD←LT(C_8)	1–0.8
12	**LB**←AD←UT(C_4,C_5,C_6); **MB**←AD←LT(C_8,Th_1); **PB**←PD←UT(C_6), PD←MT(C_7), PD←LT(C_8)	1–0.8
13	**LB**←AD←UT(C_5), AD←MT(C_6,C_7); **MB**←AD←LT(C_8,Th_1); **PB**←PD←MT(C_6,C_7), PD←LT(C_8)	1–0.8
14	**LB**←AD←UT(C_5,C_6), AD←LT(C_7); **MB**←AD←LT(C_8,Th_1); **PB**←PD←UT(C_5,C_6), PD←LT(C_7)	1–0.8
15	**LB**←AD←UT(C_5,C_6), AD←LT(C_7); **MB**←AD←LT(C_8,Th_1); **PB**←PD←UT(C_5,C_6); PD←LT(C_7,C_8)	1–0.8
16	**LB**←AD←UT(C_5,C_6), AD←MT(C_7); **MB**←AD←LT(C_8,Th_1); **PB**←PD←UT(C_5,C_6), PD←MT(C_7), PD←LT(C_8)	1–0.8
17	**LB**←AD←UT(C_5,C_6), AD←MT(C_7); **MB**←AD←LT(C_8,Th_1); **PB**←PD←MT(C_7), PD←LT(C_8)	1–0.8
18	**LB**←AD←UT(C_5,C_6), AD←MT(C_7), AD←LT(C_8); **MB**←AD←LT(C_8,Th_1); **PB**←PD←UT(C_5,C_6), PD←MT(C_7)	1–0.8
19	**LB**←AD←UT(C_5,C_6), AD←MT(C_7), AD←LT(C_8); **MB**←AD←MT(C_7), AD←LT(C_8,Th_1); **PB**←P-D←UT(C_6), PD←MT(C_7), PD←LT(C_8)	1–0.8
20	**LB**←AD←UT(C_5,C_6), AD←MT(C_7), AD←LT(C_8); **MB**←AD←MT(C_7), AD←LT(C_8,Th_1); **PB**←P-D←MT(C_7), PD←LT(C_8)	1–0.8

Note: **LB**, lateral bundle; **MB**, medial bundle; **PB**, posterior bundle; AD, anterior division; PD, posterior division; UP, upper trunk; MT, middle trunk; LT, lower trunk; C_4, C_5, C_6, C_7, C_8, Th_1, and Th_2, roots (ventral branches of spinal nerves).

The literature reports isolated cases of middle trunk formation by the roots of C_7 and C_8 and lower trunk formation by Th_1 [17, 18]. However, we did not identify any such variants. We did find a variant of middle trunk formation by roots C_6 and C_7, which occurred in 1.7% of cases. The roots of C_4 and C_5 form the upper trunk of one fetal plexus, whereas the roots of Th_1 and Th_2 form the lower trunk [11]. In our studies, we found only one case (0.8%) of a variant of upper trunk formation by the two roots C_4 and C_5. The literature describes a case of posterior trunk formation by root Th_1 [15], which was not found in our study.

Three variants of brachial plexus trunk divisions relative to the clavicle were identified: above in 24.5% of cases, behind in 57.9%, and below in 17.6%. These variations are associated with the location of the subclavian artery and its branches [1]. No information about the low formation of divisions was found in the literature. In general, the data obtained are consistent with the known information that trunk divisions are less prone to morphological variability [26].

Trunk divisions contribute to bundle formation to varying degrees in the distal direction. Our data show that the upper bundle is formed by the anterior divisions of the upper and lower trunks, the medial bundle by the anterior division of the lower trunk, and the posterior bundle by the posterior divisions of the upper, middle, and lower trunks in 82.6%–94.2% of cases. According to P. Chaudhary et al. (2014), this variant occurs in 93.3%–95% of cases [8]. The literature describes a variant in which the posterior bundle is formed solely by the posterior divisions of the upper and middle trunks in 9% of cases [18, 22, 32]. We observed this variant in 9.9% of cases. The posterior bundle was formed by the posterior divisions of the upper and lower trunks in 4.2% of cases and by the middle and lower trunks in 3.3% of cases.

Macromicroscopic intramural dissection revealed unequal variability in the formation of brachial plexus bundles with respect to spinal nerve roots. Our data indicate that the lateral bundle is formed by roots C_5, C_6, and C_7, the medial bundle by roots C_8 and Th_1, and the posterior bundle by roots C_6, C_7, and C_8 in 83.2%–91.6% of cases. In a 2014 study, P. Chaudhary et al. observed rare variants of lateral bundle formation by roots C_4, C_5, C_6, and C_7 and medial bundle formation by roots C_6, C_7, C_8, and Th_1 [8]. Our data show that the first variant was observed in 7.6% of cases, whereas the second variant was not observed. According to [28], in a rare case, the lateral bundle is formed by the anterior divisions of three trunks (C_4, C_5, C_6, and C_7), the medial bundle is formed by the anterior divisions of two trunks (C_7, C_8, and Th_1), and the posterior bundle is formed by the posterior divisions of three upper trunks (C_4, C_5, C_6, and C_7). These structural features were previously unknown.

According to our data, the average frequency of nerve fiber participation in the formation of all three bundles of the brachial plexus is as follows: C_4 was observed in 2.5%; C_5, 34.8%; C_6, 66.1%; C_7, 66.4%; C_8, 64.2%; Th_1, 33.3%; and Th_2, 0.8%. Therefore, injuries to roots C_6, C_7, and C_8 are theoretically the most dangerous because they can considerably disrupt the function of the spinal cord and upper limb muscles.

The brachial plexus elements were found to vary in structure depending on their distance from the spinal cord. Brachial plexus formation by the roots of spinal nerves resulted in the identification of three variants, whereas seven variants were identified for trunks, three for divisions, and 12–16 for bundles. In total, 20 variants of the general structure were identified. The increase in variants in the distal direction is due to numerous factors that influence the formation of brachial plexus elements, such as vessels, ligaments, muscles, and bones. These factors have their own structural variants, which ultimately result in various brachial plexus structures.

The observed regularity is consistent with and can be explained by the general evolutionary model of brachial plexus formation [35]. This model suggests that the embryonic growth of axons in the arm embryo is associated with the variability of adult morphological structures. The complex structure of the brachial plexus, which includes fusions, entanglements, and divisions of nerve fibers, arises in response to differences in the location of morphological obstacles.

After analyzing the results, it is strategically advisable to first identify the structural variants of all brachial plexus elements (root, trunk, division, and bundle) during anatomical and clinical examination. Then, we determine the common variant characteristic of a given person [27]. This approach enables clinicians to comprehensively and accurately understand the brachial plexus structure. This understanding can aid in diagnosing the location of a lesion and explaining disease symptoms. The results obtained should be compared with the existing detailed and complete classification of brachial plexus variants [26].

To visualize the identified variants, we propose a reverse system of their coding in the following direction: bundle ← division ← trunk (root). The reverse coding of the classical variant (occurring in 65.3%) of the brachial plexus structure is as follows: The code (variant 1) is **LB**←AD←UT(C_5,C_6), AD←MT(C_7); **MB**←AD←LT(C_8,Th_1); **PB**←PD←UT(C_6), MTPD(C_7), PD←MT(C_8). This code can be decoded as follows: The lateral bundle is formed by the anterior division of the upper trunk, which includes nerve fibers from roots C_5 and C_6, as well as the anterior division of the middle trunk with fibers from root C_7. The medial bundle is formed by the anterior division of the lower trunk, which includes fibers from roots C_8 and Th_1. The posterior bundle comprises fibers from the posterior divisions of the upper, middle, and lower trunks and fibers from roots C_6, C_7, and C_8.

This coding system clearly displays rare variants of the brachial plexus structure. For instance, variant 20, presented in Table 1, is described as follows: The lateral bundle is formed by the anterior division of the upper trunk, which includes nerve fibers from roots C_5 and C_6, the anterior division of the middle trunk with fibers from root C_7, and the anterior division of the lower trunk with fibers from root C_8. The medial bundle is formed by the anterior division of the middle trunk and root C_7, as well as the anterior division of the lower trunk and roots C_8 and Th_1. The posterior bundle is formed by the posterior division of the middle trunk and fibers from root C_7 and the posterior division of the lower trunk and fibers from root C_8. Using coding, this rare variant of the brachial plexus structure is as follows:

The code (variant 20) is **LB**←AD←UT(C_5,C_6), AD←MT(C_7), AD←LT(C_8); **MB**←AD←MT(C_7), AD←LT(C_8,Th_1); **PB**←PB←MT(C_7), PD←LT(C_8).

This system provides coding for brachial plexus variants, considering the nerve of interest in the following direction: nerve ← bundle ← division ← trunk (root). This extended coding provides a complete picture of the variant structure and considers the peripheral nerves. This information is useful for performing regional anesthesia, reconstructive surgeries, and rehabilitation measures and creating neurotrainers, neurochips, and nerve conduits.

Conclusions

1. The brachial plexus exhibits variability in its structure, with three variants of roots, seven trunks, three divisions, and 12–16 bundles.

2. The brachial plexus bundles are primarily formed by the roots of C_6 (66.1%), C_7 (66.4%), and C_8 (64.2%). The involvement of C_5 (34.8%) and Th_1 (33.3%) is half as common, whereas that of C_4 (2.5%) and Th_2 (0.8%) is extremely rare.

3. The reverse coding of variants of the brachial plexus structure in the direction of bundle ← division ← trunk (root) allows us to briefly, clearly, and completely display all morphological diversity of the human upper limb nervous system.

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