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THE SIGNIFICANCE OF ANATOMICAL AND HISTOMORPHOLOGICAL FEATURES OF PARAVERTEBRAL STRUCTURES IN THE DEVELOPMENT OF EXTRAVASCULAR COMPRESSION OF THE VERTEBRAL ARTERY

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The article is devoted to the study of anatomical and histomorphological features of the paravertebral musculofascial structures of the cervical spine and their role in the development of extravascular compression of the vertebral artery.

The aim of the study was to determine the topographic and anatomical relationships between the vertebral artery and the surrounding musculofascial structures and to assess morphological changes in paravertebral formations that may contribute to vascular compression.

Materials and methods. A complex anatomical and histological study of paravertebral formations of the cervical region was performed. Particular attention was paid to the spatial relationships between the vertebral artery and the prevertebral muscles.

Results. It was established that the V1 segment of the vertebral artery is located within a complex musculofascial environment formed by the longus colli muscle, longus capitis muscle, scalene muscles, and intertransverse muscles. The most pronounced potential compressive effect on the artery was observed from the inferior oblique portion of the longus colli muscle, whose fibers surround the anterior and medial surfaces of the vessel. Histological examination revealed structural changes in paravertebral muscles characterized by fibrotic transformation, sclerosis, and hyalinization, indicating degenerative remodeling of skeletal muscle tissue. Such structural alterations are accompanied by increased proportion of connective tissue components, formation of fibrotic areas, and alterations in the microcirculatory component of tissues.

Conclusion. The obtained findings suggest that a combination of anatomical features of paravertebral formations and degenerative histomorphological changes in surrounding tissues may create conditions for extravascular compression of the vertebral artery. These morphological characteristics should be taken into account when studying the pathogenesis of vertebral artery compression syndrome and during clinical assessment of patients with vertebrobasilar circulation disorders.

Keywords: vertebral artery, vertebral artery compression syndrome, extravascular compression, paravertebral muscles, cervical spine.

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ЗНАЧЕННЯ АНАТОМО-ГІСТОМОРФОЛОГІЧНИХ ОСОБЛИВОСТЕЙ ПАРАВЕРТЕБРАЛЬНИХ УТВОРЕНЬ ШИЙНОГО ВІДДІЛУ ХРЕБТА У ФОРМУВАННІ СИНДРОМУ КОМПРЕСІЇ ХРЕБТОВОЇ АРТЕРІЇ

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Стаття присвячена дослідженню анатомо-гістологічних особливостей паравертебральних утворень шийного відділу хребта та їх ролі у формуванні екстравазальної компресії хребтової артерії. Метою дослідження було визначення топографо-анатомічних взаємовідношень хребтової артерії з м'язово-фасціальними структурами та оцінка морфологічних змін паравертебральних утворень. Встановлено, що найбільш виражений компресійний вплив на судину відзначено з боку нижньо-навскісної порції довгого м'яза шиї. Гістологічний аналіз виявив ознаки дегенеративно-дистрофічного ремоделювання м'язової тканини з розвитком фіброзу, склерозу та гіалінозу. Отримані результати свідчать, що поєднання анатомічних особливостей паравертебральних утворень та їх морфологічних змін може відігравати важливу роль у формуванні екстравазальної компресії хребтової артерії.

Ключові слова: хребтова артерія, синдром компресії хребтової артерії, екстравазальна компресія, паравертебральні м'язи, шийний відділ хребта.

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Стаття поширюється на умовах ліцензії

Introduction

Among spinal disorders, approximately 10–20 % are represented by conditions with specific clinical manifestations, whereas 80–90 % are attributed to degenerative-dystrophic lesions that often lack clear clinical or radiological signs [1; 2]. The cervical spine is characterized by high mobility and significant dynamic loading, which determine the structural features of the vertebrae, intervertebral discs, ligamentous apparatus, and paravertebral musculofascial structures [3].

The anatomical relationships between the vertebral artery (VA) and the surrounding muscular, fascial, and osseous structures of the cervical region create conditions for potential mechanical impact on the vessel. In particular, the prevertebral and scalene muscles, together with fascial components, form a musculofascial space through which the V1 segment of the VA passes. Morphological alterations in these tissues, including degenerative-dystrophic transformation of muscle tissue and connective tissue remodeling, may modify the topographic and anatomical conditions of vascular function [4; 5].

Disturbances of blood flow in the vertebrobasilar system associated with vertebral artery compression syndrome (VACS) account for 25–30 % of all acute cerebrovascular events and nearly 70 % of transient ischemic attacks. Notably, approximately 65 % of pathological changes are localized in the extracranial segments of the VA [6]. At the same time, the anatomical and histological features of paravertebral formations remodeling that may contribute to the development of extravascular compression of the VA remain insufficiently studied.

The aim of this study was to determine the anatomical and histomorphological features of the paravertebral musculofascial structures of the cervical spine and to assess their role in the development of VACS.

Materials and Methods

The study had a comprehensive clinical and morphological design and was aimed at investigating anatomical and histological changes in the paravertebral musculofascial structures of the cervical spine that may contribute to the development of extravascular compression of the VA.

The clinical part of the study included 1,118 patients presenting with clinical manifestations of vertebrobasilar insufficiency associated with degenerative-dystrophic changes of the cervical spine. Patient examination and treatment were conducted at Kyiv City Clinical Hospital No. 8. The study was performed in accordance with the principles of the Declaration of Helsinki [7]. The study protocol was approved by the local Bioethics Committee of Bohomolets National Medical University (Protocol No. 191, January 27, 2025). Written informed consent was obtained from all participants prior to inclusion in the study.

Based on clinical and pathogenetic features of disease progression, patients were divided into two groups. Group I consisted of 600 patients with a compression-spastic form of the syndrome, characterized by predominant functional spastic alterations of the musculofascial structures leading to positional compression of the VA. Group II included 518 patients with a spastic-organic form, in which, alongside muscle tone disturbances, pronounced structural changes in connective tissue were observed, contributing to organic components of vascular stenosis.

All patients underwent a comprehensive clinical neurological examination with assessment of symptoms characteristic of VACS, including dizziness, headache, coordination disturbances, instability, visual impairment, and other manifestations of vertebrobasilar insufficiency [8].

The morphological part of the study comprised both anatomical and histological analyses. The anatomical study was performed on 64 cadaveric specimens of the cervical spine obtained from adult individuals without signs of traumatic injury or significant vascular pathology. Layer-by-layer dissection of cervical tissues was carried out with isolation of the VA in the V1 segment, followed by analysis of its topographic and anatomical relationships with adjacent musculofascial formations. The spatial relationships between the artery and the longus colli muscle, longus capitis muscle, anterior and middle scalene muscles, as well as the intertransverse muscles of the cervical spine were evaluated. Variants of the anatomical course of the VA in the V1 segment were classified into three types (Var. 1, Var. 2, Var. 3) depending on the characteristics of its origin from the subclavian artery, its relationship with the scalene muscles, and the level of entry into the transverse foramen of the cervical vertebrae.

The use of different types of material was determined by the specific objectives of the morphological analysis: cadaveric specimens were used to assess the topographic and anatomical relationships of the VA with relationships of the VA with paravertebral formations, whereas biopsy material obtained from patients with VACS allowed the evaluation of pathological histomorphological changes associated with the development of the compression syndrome.

Histological examination was performed on 86 biopsy specimens of paravertebral muscles obtained during surgical interventions in patients with VACS. Tissue samples were fixed in 10 % neutral formalin, followed by standard histological processing with paraffin embedding and sectioning at a thickness of 5–7 μm. Sections were stained with hematoxylin and eosin [9] and using the Van Gieson method [10] to differentiate muscular and connective tissue components. Microscopic evaluation was carried out using a light microscope (Olympus BX43, Olympus, Japan).

Morphological assessment was performed using a semi-quantitative analysis of structural changes in muscle and connective tissues, including evaluation of the degree of fibrosis, dystrophic alterations of muscle fibers, vascularization, and tissue remodeling. The analysis was conducted across multiple fields of view at different magnifications.

Research results and their discussion

Anatomical mechanisms of extravascular compression of the V1 segment of the VA

The anatomical study demonstrated that the musculofascial environment of the VA in the V1 segment is formed by the anterior, middle, and posterior scalene muscles, the longus colli muscle, the longus capitis muscle, the intertransverse muscles, and the omohyoid muscle.

It was established that the longus colli muscle forms the principal musculofascial bed for the V1 segment of the VA. The most pronounced potential compressive and deforming effect on the vessel was observed from its inferior oblique portion, whose fibers enveloped the anterior and medial surfaces of the VA (Fig. 1).

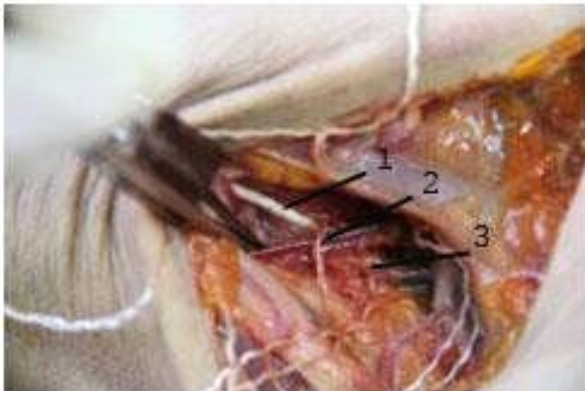


Fig. 1. Topographic and anatomical relationships of the vertebral artery with paravertebral formations in the V1 segment

Note: medial part of the scaleno-vertebral canal: longus colli muscle (1); vertebral vein (2); vertebral artery (3).

The longus colli muscle, together with the prevertebral fascia, the anterolateral surfaces of the C6-C7 vertebral bodies, and the intervertebral discs, forms a musculofascial compartment for the VA in the distal part of the V1 segment. Structurally, the longus colli muscle was divided into three parts: (1) the medial vertical portion, originating from the vertebral bodies of C5-T3 and attaching to the anterior surfaces of C3-C2 and the anterior tubercle of the atlas; (2) the superior oblique portion, originating from the anterior tubercles of the transverse processes of C2-C5 and attaching to the body of C2 and the anterior tubercle of the atlas; (3) the inferior oblique portion, originating from the vertebral bodies of T1-T3 and attaching to the anterior tubercles of the transverse processes of C5-C7.

In Var. 1 and Var. 2 of VA origin, the medial vertical portion of the longus colli muscle did not exert a significant compressive or deforming effect on the vessel wall within the V1 segment. In contrast, in Var. 3, deformation of the arterial wall was observed in cases of high entry of the artery into the transverse foramen at the C4-C5 level (6 females and 6 males), which was associated with contact between the vessel and the tendinous component of the medial vertical portion of the longus colli muscle. At the C5-C6 level, these cases were frequently accompanied by anatomical variations of the transverse foramen, including atresia or the presence of a bony septum resulting from incomplete fusion of the anterior and posterior elements of the transverse process. Less pronounced deformation of the arterial wall was observed in three cases (1 female and 2 males) where a high entry into the transverse process canal was not associated with incomplete fusion.

The superior oblique portion of the longus colli muscle generally did not contribute to compression of the VA in Var. 2, as the artery entered the transverse process canal at the C6 level, corresponding to typical anatomical relationships. However, in some specimens, variations in muscle attachment were observed: in 11 females and 14 males, its fibers originated from the transverse process of C7, and in 2 females and 3 males, individual bundles extended to the costotransverse junction of the first rib and T1. These variations could potentially contribute to compressive and deforming effects on the VA even in the absence of physiological muscle tone.

In 17 males and 15 females with Var. 2, in the absence of compression from the superior oblique portion of the longus colli muscle, an abnormal attachment of the longus capitis muscle to the transverse process of C7 was observed. With a more lateral attachment, its musculotendinous bundles arched around the medial and inferior surfaces of the VA, forming a groove-like deformation of the vessel wall in the shape of a semicircular spiral extending from the lateral surface of the artery at the C6 level to the posteromedial surface at the C7 level.

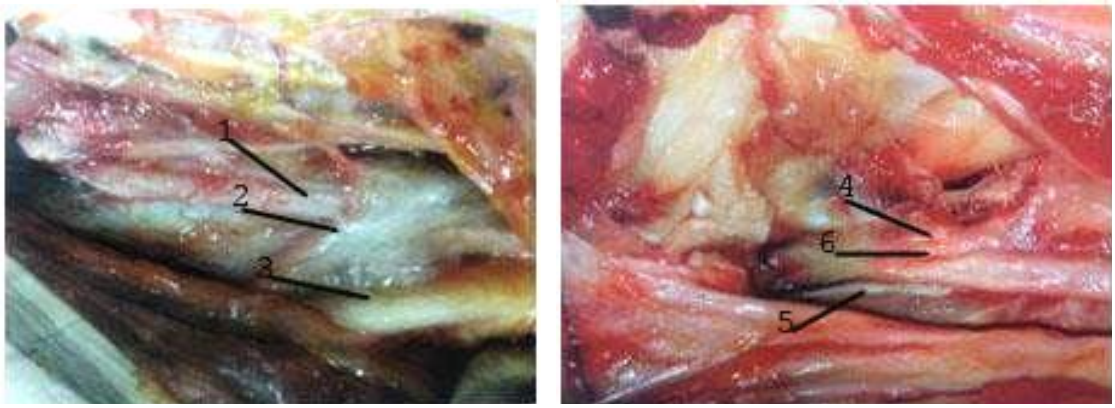
Variants of abnormal attachment of the longus capitis muscle were also identified in cases with Var. 1 type of VA origin. In anatomical specimens, muscle bundles originated from the anterior tubercles of the transverse processes of C7 in 7 females and 5 males, and from the transverse process of T1 and the first rib at the costotransverse joint in 2 females and 3 males. Despite these variations, a compressive and deforming effect of the abnormally positioned bundles of the musculus longus capitis on the V1 segment of the VA was observed in only 5 out of 17 specimens, predominantly in cases where the tendinous portion of the muscle extended to the level of the first rib and the transverse process of T1.

In Var. 1 of VA origin, an additional factor reducing compressive influence was the characteristic origin of the artery from the posterior wall of the subclavian artery, whereas the thyrocervical trunk originated opposite to or medial to the orifice of the VA.

In 7 females and 5 males with Var. 1, the superior oblique portion of the longus colli muscle extended to the transverse process of C7 but did not produce a pronounced compressive or deforming effect on the arterial wall. Its fibers interwove with those of the intertransverse muscles and extended to the level of the transverse process of T1, forming a musculofascial layer 2–3 mm thick, fused with the prevertebral fascia. Under these conditions, the distal portion of the V1 segment, at a distance of 1–1.5 cm proximal to the beginning of the V2 segment (lower border of the transverse process of C7), was located within a so-called muscular “groove,” where the most pronounced deformation of the vessel contour was observed.

In 12 cases (6 males and 6 females) with Var. 3 of VA origin, associated with high entry into the transverse process canal at the C4-C5 level, the superior oblique portion of the longus colli muscle together with the longus capitis muscle exerted a significant compressive and deforming effect on the anterior, lateral, and posterior walls of the VA. The degree of deformation increased in the presence of anomalous non-fusion of the anterior and posterior elements of the transverse process at C6 or at the C5-C6 level.

It was also established that a high level of entry of the VA into the transverse process canal was associated with topographic elongation of the V1 segment, whereas the V2 segment was relatively shorter (Fig. 2).



a **b**

Fig. 2. Features of the topographic and anatomical relationships of the vertebral artery in cases of anomalously high entry into the transverse process canal

Note: formation of compressive interaction involving an anomalous transverse process of C6, the longus colli muscle, and the longus capitis muscle: a – vertebral artery (1), stellate ganglion (2), primary trunk of the C7 brachial plexus (3); b – transverse process tubercle of C5(4), longus colli muscle (5), deformed vertebral artery (6).

This anatomical configuration creates conditions for an increased likelihood of positional extravascular compression, with the V1 segment remaining the most vulnerable.

The primary anatomical factor responsible for the compressive and deforming effect on the wall of the VA in the V1 segment was the inferior oblique portion of the longus colli muscle, the role of which was evident across all variants of VA origin (Var. 1–3). The most characteristic features of its topography were observed in Var. 2, which was the most prevalent.

Muscle fibers originated from the anterior surface of the transverse process of C6, passed beneath the fibers of the longus capitis muscle, partially interwove with the intertransverse and anterior scalene muscles, and extended caudally in a descending spiral pattern. In this configuration, they enveloped the anterior and medial surfaces of the VA and attached to the vertebral bodies of C6-C7-T1, forming a crescent-shaped muscular enclosure. As a result, the VA was located within a spiral musculofascial sheath, leading to compressive deformation of its anterior, medial, and partially posterior walls (Fig. 3A, 3B).

Observations indicate that this mechanism constitutes the principal impingement syndrome of the VA, the severity of which may increase during contraction of the cervical muscles under dynamic movements or static loading.

In Var. 3 of VA origin, a similar pattern was observed in 7 cases (4 males and 3 females) associated with non-fusion of the transverse process of C6. Under these conditions, compression of the posterior wall of the VA was predominantly observed, and less frequently of the medial wall. This was attributed to the attachment of fibers of the inferior oblique portion of the longus colli muscle to a protruding transverse process formed as a result of incomplete fusion of its costal and transverse components.

The intertransverse muscle group also contributed to the formation of extravascular compression; however, its role varied depending on the variant of VA origin: it was most pronounced in Var. 1, less significant in Var. 2, and minimal in Var. 3. In Var. 1, the intertransverse muscles originated from the transverse process of C7 medial to the attachment of the anterior scalene muscle and, together with the inferior oblique portion of the longus colli muscle, formed a musculofascial structure at the level of the VA entry into the



a **b**

Fig. 3. Morphological features of vertebral artery compression in the scaleno-vertebral canal during contact with the longus colli muscle

Note: after resection of the medial wall of the scaleno-vertebral canal: a – vertebral artery (1), anterior scalene muscle (2); b – longus colli muscle (3), area of the scaleno-vertebral canal of extravascular compression (4), vertebral artery (5).

scaleno-vertebral canal. Under these conditions, in 7 cases involving the left VA, pathological tortuosity with medial deviation and loop formation was observed prior to entry into the canal, which was interpreted as a compensatory mechanism aimed at reducing vascular compression.

An additional compressive factor in Var. 1 was the anterior scalene muscle, individual bundles of which could originate from the transverse process of C7, thereby exerting additional compression on both the vertebral and subclavian arteries. At the same time, the origin of the VA from the posterior wall of the subclavian artery partially mitigated this effect. In Var. 2, the compressive effect of the anterior scalene muscle was observed in all specimens; in 11 cases, its abnormal attachment to the transverse process of C7 was noted, which increased the compressive and deforming effect on the V1 segment. In contrast, in 46 specimens with Var. 2, the classical attachment of the muscle to the anterior tubercles of the transverse processes of C3-C7 was preserved, which was associated with less pronounced deformation of the vessel.

Histomorphological changes of paravertebral musculofascial structures

The next stage of the study involved biopsy-based morphological and immunohistochemical analysis of striated muscle tissue in the regions of trigger points associated with myofascial pain syndromes. Based on the obtained data, the most probable localizations of trigger zones within the musculofascial structures of the neck and shoulder girdle were identified. In addition, the morphological features of morphogenesis and pathogenesis of extravascular myofascial compression of the VA, as well as their age-related and clinical-pathohistological correlations, were established.

Histological examination demonstrated that degenerative-dystrophic changes in skeletal muscle tissue were accompanied by progressive fibrotic transformation with the formation of various types of fibrotic connective tissue. The analysis specifically focused on fibrotic connective tissue, which reflects processes of sclerotic degeneration of muscle fibers, in contrast to the organized connective tissue of tendons and ligaments.

Within areas of fibrotic remodeling associated with muscle fiber degeneration, several morphological variants of connective tissue were identified: α – immature granulation tissue with predominance of cellular elements (fibroblasts, macrophages, histiocytes) and thin-walled vessels; β – loose connective tissue characterized by reduced cellular density and a relative increase in collagen structures; γ – dense unorganized connective tissue with thick collagen fibers, a small number of fibrocytes, and sclerosed vessels; δ – hyalinosis, characterized by the absence of cellular elements and the formation of a homogeneous, structureless mass.

To assess structural changes in paravertebral formations associated with VACS, a histomorphological analysis of biopsy material from paravertebral muscles was performed, including the identification of connective tissue types (α–δ), which reflected different variants and degrees of degenerative-dystrophic tissue remodeling (Fig. 4–8).

Histomorphological analysis of biopsy material from paravertebral formations demonstrated a sequential pattern

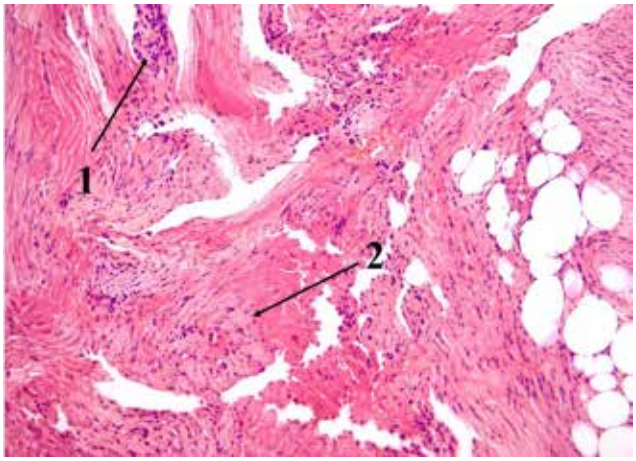


Fig. 4. Granulation connective tissue with active fibroplastic response

Note: 1 – small thin-walled blood vessels; 2 – areas of mature connective tissue with isolated fibrocytes (types α, α–β). Hematoxylin and eosin staining; magnification ×200.

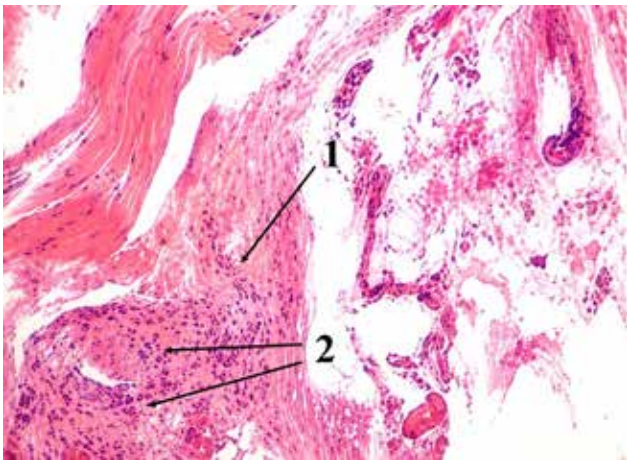


Fig. 5. Granulation remodeling of muscle tissue with active fibroplastic response and neovascularization

Note: 1 – areas of granulation tissue with active cellular response; 2 – newly formed blood vessels (type α). Hematoxylin and eosin staining; magnification ×200.

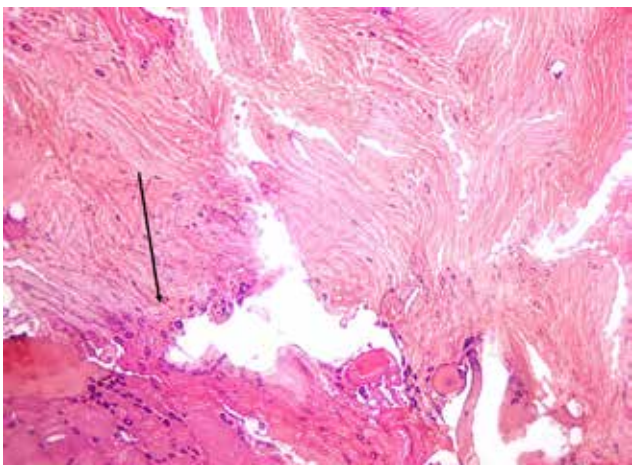


Fig. 6. Fibrotic remodeling of muscle tissue with formation of dense irregular connective tissue

Note: broad areas of mature connective tissue (type γ). Hematoxylin and eosin staining; magnification ×200.

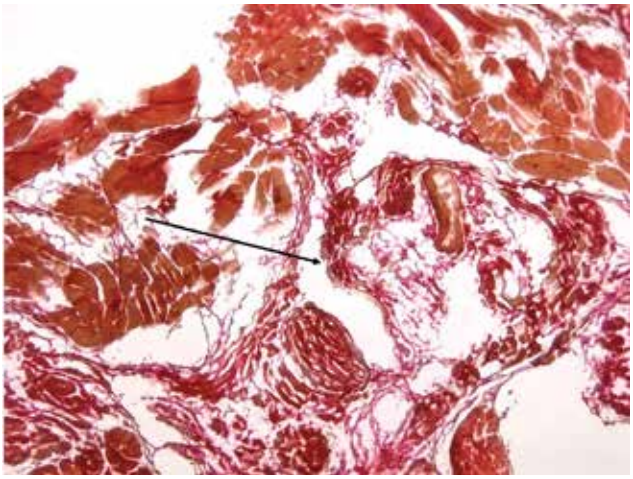


Fig. 7. Perivascular formation of loose fibrous connective tissue

Note: perivascular proliferation of loose fibrous connective tissue (type β). Van Gieson staining; magnification ×400.

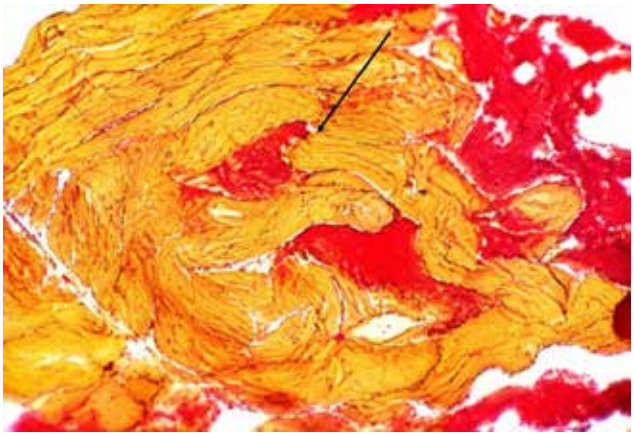


Fig. 8. Hyalinosis and sclerotic remodeling of muscle tissue

Note: mature connective tissue with areas of hyalinosis between muscle fiber bundles (type γ–δ). Van Gieson staining; magnification ×400.

of structural remodeling of skeletal muscle tissue associated with degenerative-dystrophic changes. The identified morphological variants of connective tissue reflected different stages of remodeling, encompassing a spectrum of alterations from early fibroplastic processes with the formation of granulation and loose fibrous connective tissue (types α–β) to pronounced sclerotic transformations with the development of dense irregular connective tissue and areas of hyalinosis (types γ–δ). Microscopically, the progression of the degenerative process was accompanied by a reduction in the number of functionally active muscle fibers, an increase in the proportion of collagen structures, formation of fibrotic areas, and alterations in the microcirculatory component of the tissue. These changes indicate a gradual loss of elastic properties of the paravertebral musculofascial formations and their transition to a denser fibrotic-sclerotic state.

The obtained morphological findings are important for understanding the mechanisms of extravascular compression of the VA. Under normal anatomical conditions, the musculofascial structures of the cervical region provide a dynamic environment for the V1 segment of the vertebral artery; however, with the development of fibrotic remodeling, their ability to deform and relax is reduced. The formation of dense connective tissue and hyalinosis may contribute to increased rigidity of the musculofascial complex, creating additional conditions for narrowing the space surrounding the vessel and enhancing mechanical pressure on its wall.

Thus, the results of the histological study complement the findings of the anatomical analysis and indicate that the development of VACS may be associated not only with the topographic and anatomical features of the vessel and paravertebral formations but also with structural remodeling of the musculofascial environment, which alters its mechanical properties.

The obtained results confirm the important role of anatomical and topographic relationships of paravertebral formations of the cervical spine in creating conditions for the development of extravascular compression of the VA. The study demonstrated that the V1 segment of the artery is located within a complex musculofascial environment formed by the longus colli muscle, longus capitis muscle, scalene muscles, and intertransverse muscles. Similar anatomical relationships have been described by McDavid et al. [11], who noted that prevertebral muscles form a functional musculofascial canal through which the proximal segment of the VA passes. Variability in their topography may alter spatial relationships between the vessel and surrounding structures, creating conditions for mechanical compression. Comparable observations were reported by Furtado et al. [12], emphasizing the role of anatomical variations of the VA and surrounding musculofascial structures in vertebrobasilar hemodynamic disturbances.

An important complement to the anatomical findings is provided by the histological analysis of paravertebral muscles. The identified structural changes, including fibrosis, sclerosis, and hyalinosis, indicate the development of degenerative-dystrophic remodeling of muscle tissue. The formation of different morphological types of connective tissue reflects consecutive stages of this process and is associated with decreased elasticity and increased density of musculofascial structures. Similar changes in skeletal muscle under chronic degenerative conditions have been described in morphological studies by Hsiao et al. [13] and Dubuisson et al. [14], highlighting that fibrotic transformation can significantly alter biomechanical properties of muscle tissue.

From a clinical perspective, the combination of anatomical variants of the VA with degenerative changes in paravertebral formations may create conditions for persistent extravascular compression of the vessel. Similar mechanisms underlying VACS have been described in reviews and meta-analyses by Valenzuela-Fuenzalida et al. [4], which emphasize the importance of musculofascial factors in vertebrobasilar circulation disorders.

Thus, the results of the present study indicate that the development of extravascular compression of the VA is multifactorial and associated both with the topographic features of paravertebral muscles and with

their morphological remodeling. The identified structural changes may be considered a morphological basis for the development of VACS and should be taken into account in the clinical assessment of patients with manifestations of vertebrobasilar insufficiency.

Conclusions

It was established that the V1 segment of the VA has complex topographic and anatomical relationships with the paravertebral musculofascial formations of the cervical spine. The most pronounced potential compressive effect on the vessel was associated with the inferior oblique portion of the longus colli muscle, while the anatomy of the VA and patterns of muscle attachment may modify the conditions of its spatial positioning.

Histomorphological examination of paravertebral muscles in patients with VACS revealed degenerative-dystrophic tissue remodeling with the development of fibrotic and sclerotic changes and hyalinosis, accompanied by an increased proportion of connective tissue and decreased elasticity of the musculofascial structures.

The combination of anatomical features of paravertebral formations and their structural remodeling may create morphological prerequisites for the development of extravascular compression of the vertebral artery and the formation of VA compression syndrome.

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