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ORIGINAL PAPER

The Ligamentum condylicum posterius as a precursor structure of the Processus condylicus posterior, another Proatlas-Manifestation of the human occipital bone

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Abstract

This article presents the results of a dissection series investigating a previously neglected ligamentous structure attached to the human occipital bone, the Ligamentum condylicum posterius or posterior condylar ligament, and relates these results to the manifestation of a likewise poorly recognized occipital bony variation, the Processus condylicus posterior. The dissection of 50 human cranio-cervical junctions revealed the existence of the posterior condylar ligament in 98% of all cases, sometimes containing free elongated ossicles and osseous spurs at the insertion points at the occipital bone. In two cases the osseous formation of a Processus condylicus posterior became apparent (4%), which further provided the opportunity to study the behaviour of the ligament in these cases. In this article, we show and discuss that the posterior condylar ligament and osseous structures possibly derive from tissue that originates from the material of the dorsal arch of the Proatlas, a rudimentary vertebra between occipital bone and atlas. For this purpose, the Ponticulus atlantis posterior as another Proatlas-manifestation, whose origin from the dorsal Proatlas-arch is widely accepted in literature, is considered. This bony variant was found in 11 specimens (22%) in the present study and further served to classify and interpret the findings of the much rarer Processus condylicus posterior. As a result of this dissection series and a review of literature on this understudied topic, a typology of manifestations of the posterior condylar ligament, Processus condylicus posterior and related structures like free ossicles has been introduced.

KEYWORDS

arcuate foramen, craniocervical joint, Ligamentum condylicum posterius, occipital vertebra, Ponticulus posterior, posterior condylar ligament, Proatlas, Processus condylicus posterior

1 | INTRODUCTION

The transition of the occipital bone to the first and second cervical vertebrae is a morphologically highly variable region. In the past 200 years there has been great effort to describe and explain the manifestations of additional osseous structures at the craniocervical junction in man leading to a considerable amount of research being published in this fascinating area of morphology.

The fact that these osseous variants appear in a regular manner can be explained by the concept of the manifestation of a rudimentary vertebra between occiput and atlas: the Proatlas (Albrecht, 1880) or 'Occipitalwirbel' (=occipital vertebra), whereby most authors use these two terms synonymously (e.g. Brocher, 1955; Ganguly & Singh-Roy, 1965; Hayek, 1923).

This concept is based on the fact that at the craniocervical junction, due to lack of regression, remnants of such a vertebra can remain. These remnants are formed by the caudal half of the last occipital and the cranial half of the first cervical sclerotome (Hayek, 1927) during embryological development. For a comprehensive depiction of the embryological processes of the craniocervical junction and the manifestation of various accessory bony structures see O'Rahilly and Müller (1984), Müller and O'Rahilly (1994, 2003), Prescher (1997) and Menezes (2008). An overview of the various possibilities of manifestation deriving from different Proatlas-substructures has been published before (Prescher, 1997).

FIGURE 1 Atlanto-occipital joint in laterocaudal view: Dorsolateral to the occipital condyle a Processus condylicus posterior (arrowhead) rises and points toward the slope posterior to the condylar fossa; macerated occiput and atlas of a 93-year-old woman

This subject of Proatlas-manifestation, the clinical phenomena potentially resulting from it and their treatment is part of modern medicine. Always new findings of both morphological (Tsuang et al., 2011; Spittank et al., 2016) and clinical investigation (Hedequist & Mo, 2020; Menezes & Dlouhy, 2020; Montrisaet & Petcharunpaisan, 2020; Sato et al., 2019) continue to enrich this field of research.

The appearance of parts of this additional vertebra has also been described as various constant or inconstant manifestations in different species other than human, for example, *Erinaceus europaeus*, *Sphenodon* (*Hatteria*) *punctatus* and members of the order *Crocodilia* (Albrecht, 1880, 1883; Baur, 1886; Dollo, 1889).

This study focuses on the manifestation of an osseous process arising dorsolaterally to the occipital condyles that spans the condylar fossa and points towards the retrocondylar area lateral to the margin of the foramen magnum, respectively, towards the posterior arch of the atlas but without reaching them: Processus condylicus posterior (see Figures 1 and 2). This supernumerary structure is not mentioned in the standard references of osseous variants of the human skull and upper cervical spine (Bergmann, Afifi & Miyauchi, 2015; Berry & Berry, 1967; Hauser & de Stefano, 1989; Torklus & Gehle, 1975) thus further research is needed. Firstly described by Bolk (1922) this osseous anomality has been further examined and interpreted by Hayek (1927) as a manifestation of the posterior part of the dorsal Proatlas arch. Bystrow (1931) reported on four similar cases of such osseous processes, being the first to describe a bilateral manifestation. Fischer (1959) documented this osseous variety in X-ray tomography technique whereby Fischer and his colleague Schmidt first termed this structure as Processus condylicus posterior (Schmidt & Fischer, 1960).

Within the framework of a larger maceration series, several cases of this type have also been described in our institute (Prescher, 2014). However, a detailed examination of this bony anomaly has

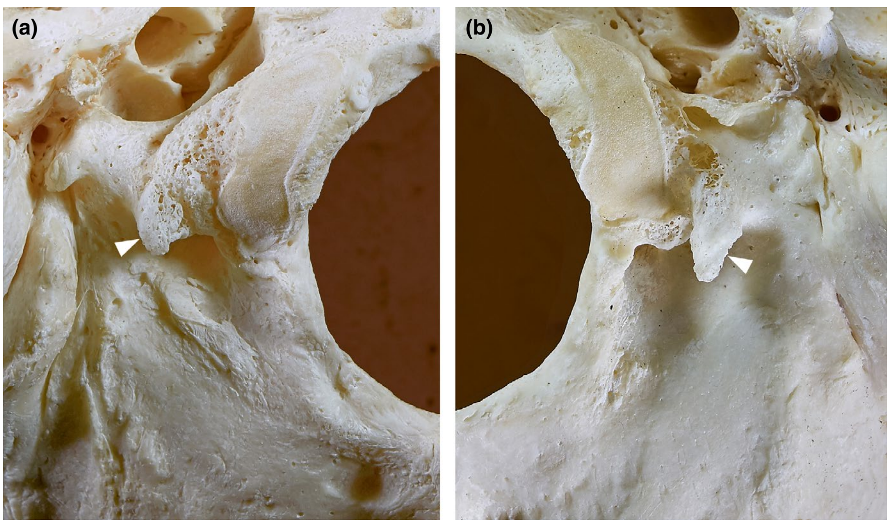

FIGURE 2 (a, b) Caudal view on two different skullbases: The arrowheads mark an accessory bony process posterolateral of the occipital condyles: (a) Processus condylicus posterior dexter, macerated occiput of an 89-year-old man; (b) Processus condylicus posterior sinister, macerated occiput of a 93-year-old woman

FIGURE 3 Occipital pericondylar region, laterodorsal view on left side of the Foramen magnum; the arrowheads mark a fibrous strand bridging the condylar fossa: Posterior condylar ligament, the white asterisk marks the jugular foramen; partly macerated occiput of an 82-year-old man

not been carried out so far and is not available to us from any other source.

Additionally, in the context of regular maceration processes of human specimens in our institute, we could observe a rough fibrous structure, that bridges the condylar fossa (see Figure 3). This ligament, which we refer to as Ligamentum condylicum posterius or posterior condylar ligament in reference to the bony process, seems to be part of the posterior portion of the atlantooccipital membrane. Its topography corresponds to the formerly described Processus condylicus posterior. An early description of this fibrous structure can be found at Luschka (1862), who attributes to it the protection of the condylar emissary vein, which emerges from the condylar fossa.

This information led us to the central question and the starting point for the present study, if this fibrous structure is homologous to the osseous process and therefore provides the tissue of origin for the osseous anomaly. Furthermore, we assumed that we would reveal further details of the Processus condylicus posterior during the examination of the preparations in order to classify this anomaly in the context of further Proatlas-manifestations.

2 | MATERIALS AND METHODS

For the present study, the craniocervical junction of 50 fresh/frozen human specimens have been examined. All specimens are part of the body donation program of the Institute for Molecular and Cellular Anatomy (MOCA) of the RWTH University Aachen. The group of examined body donors consists of 28 female and 22 male Caucasian individuals with a mean age of 80 years (female: 81; male: 78) and an age range between 62 and 96 years. Because of possible bias effects, all specimens were chosen by following conditions: (1) There are no surgical operations in the region of atlanto-occipital junction and cervical vertebrae during lifetime, (2) the region of interest is free of any preparation and is not manipulated in any way before, (3) the specimen is not fixated so that all structures can be potentially assessed later after maceration process. This last condition can be explained by the fact that in our institute the best maceration results were obtained with maximum protection of even the finest bone structures when macerating unfixed tissue due to shorter maceration periods. This procedure has proven successful in the examination of the craniocervical junction (e.g. Prescher, 1997) and was also applied accordingly in this study.

2.1 | Stratigraphic preparation

The stratigraphic preparation has been performed after exarticulating the cervical spine between C4/C5 or C3/C4 respectively. After removing cutis, subcutis and the superficial layer of muscles of the neck (trapezius muscle and autochthonous back muscles), the suboccipital muscles have been dissected to identify the borders of the occiput, atlas and axis. After cleaning the dorsal arch of the atlas, the atlantoaxial joint has been dissolved by incising the cruciate ligament complex and alar ligaments allowing separation of lower cervical spine from atlas and occiput. For this step, the neck was divided into an anterior and a posterior section, the latter containing mainly cervical vertebrae and musculature, by dissecting the prevertebral layer of the cervical fascia. The posterior section with the vertebrae other than the atlas could now be removed. In a next step, the remnants of the rectus capitis posterior major muscle have been removed and the atlantic part of the vertebral artery has been displayed, so that the posterior aspect of the atlas was clearly and completely exposed. After removing the atlas, proceeding with reasonable caution, the posterior part of the atlantoocciptal membrane with the posterior condylar ligament has been assessed.

2.2 | Maceration process

After first documentation most specimens, consisting of skull, mandible, hyoid bone and upper cervical vertebrae have been processed in warm water maceration as part of the standard procedure of the institute to gain clean osseous anatomical preparations for subsequent analysis. After the actual maceration, the preparations were degreased and, if necessary, again photodocumented.

2.3 | Storage in preservative solution

Special cases of soft tissue preparations have been fixated and stored in color preserving fixative (Jores I fixing-/Jores II storage-solution) or ethanol, making the topographic situations available for a potential later examination and further measurements.

3 | RESULTS

This dissection study of 50 atlanto-occipital joints revealed, aside from different osseous variations of atlas and occiput, that there is a constant presence of the posterior condylar ligament and a huge variety of the related osseous structures in the posterolateral condylar region of the occipital bone.

3.1 | Posterior condylar ligament

The posterior condylar ligament, a fibrous structure bridging the condylar fossa, has been found in 49 of 50 (98%) cases on both sides of the foramen magnum. Only one case showed a unilateral presence of this ligament (2%). In all cases, where the ligament has been found, it connected the osseous rim lateral to the occipital condyles, the jugular process which is part of the lateral aspect of the occipital bone, with the retrocondylar region lateral to the medio-occipital margin of the foramen magnum. Measuring the length of the ligament was impeded by the fact that both the origin and the insertion site are rather small areas to which the ligament adheres. Therefore, the shortest fibre was always measured and thus the smallest distance between the origin and insertion field. The average length of the ligament is therefore 24.5 mm with a range of 11.5–45.5 mm for a total of 97 measured specimens.

Notably, a different behavior regarding the vascular situation and possible fibres communicating with the capsule of the atlantooccipital joint could be observed, when looking at both sides of the foramen magnum.

In n = 7 cases (14%) a condylar emissary vein perforating the posterior condylar ligament could be observed. This emissary vein drains blood via the condylar foramen, which is located on the ground of the condylar fossa and connects the intracranial sinuses with the extra-cranial venous system. In two of these cases a perforating vein has been found bilaterally, in one further case there are two veins on one side of the foramen magnum that perforates the ligamentous tissue.

Another phenomenon, which we could observe in four out of 50 (8%) cases, is the existence of thick communicating fibers between the ipsilateral joint capsule of the atlantooccipital joint and the actual posterior condylar ligament, the strongest of which had a diameter of 0.75 mm.

3.2 | Free ossicles in posterior atlanto-occipital membrane

Due to the stratigraphic removal of tissue and the sparing of corresponding structures, free ossicles within the posterior condylar ligament were exposed in several cases during the preparation of the posterior atlanto-occipital membrane (see Figure 4). In nine cases (18%) we found such free ossicles embedded in the fibrous tissue, located between the posterior arch of the atlas and the retrocondylar region of the occiput. In two of these nine specimens these ossicles became apparent on both sides (4%). Additionally, in one of these two cases, two ossicles could be found on the left side, lying in different layers in the posterior condylar ligament. Overall, 12 free ossicles have been observed, ten on the left side versus two on the right side. The size of the ossicles varies between 1.0 to 9.0 mm in anteroposterior direction and differ in shape in detail, but have in common that all different ossicles follow the direction of the fibrous ligament by having basically an ellipsoidal to an elongated form. Figure 4 shows an example of a free ossicle lying in the posterior portion of the posterior condylar ligament (specimen of a 78-year-old woman, ossicle size 7.5 × 2.5 mm).

FIGURE 4 Posteromedial view on left side of the Foramen magnum: Free posterocondylar ossicle (*), embedded in fibrous tissue of the posterior condylar ligament (small arrow), the joint capsule (arrowheads) of the atlantooccipital joint has been separated from the ligament; specimen of a 78-year-old woman, in Jores II storage solution

3.3 | Processus condylicus posterior

An osseous process, having its basis on the rim lateral to the occipital condyle and bridging the rostral part of the condylar fossa, has been found at two skullbases (4%), one on the left and one on the right side of the foramen magnum.

3.3.1 | Case 1

The first case is the skullbase of a 93-year-old woman, that presents this anomality on the left side (see Figures 1, 2b and 5). The dissection of the fibrous structures in this region showed, that the rostral insertion of the posterior condylar ligament is attached to the point of the Processus condylicus posterior and hence the ligament can be understood as a posterior extension of the process. As depicted in

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FIGURE 5 Posterolateral view on atlanto-occipital transition: Processus condylicus posterior (arrowhead), posterior condylar ligament (small arrow), Ligamentum occipitale accessorium posterius (*) and vertebral artery; the part of the posterior oblique ligament that covers the vertebral artery in its lateral course between atlas and occipital bone has been removed; fresh specimen of a 93-year-old woman

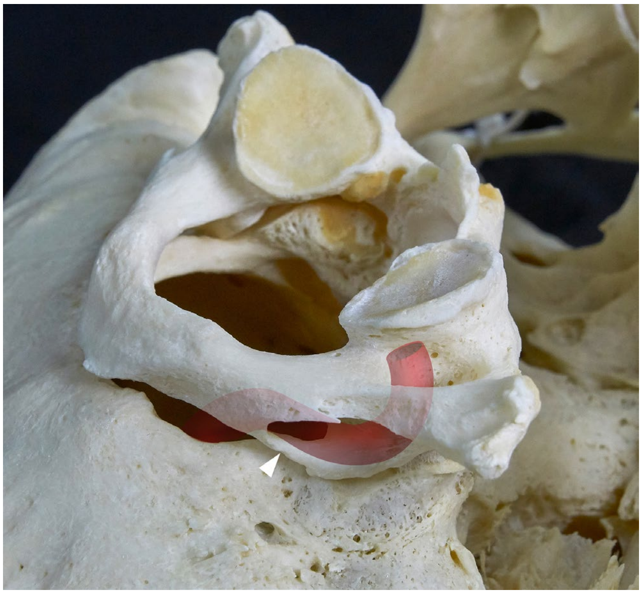

FIGURE 6 Atlanto-occipital joint in laterocaudal view: A Ponticulus atlantis posterior (arrowhead) bridges the left Sulcus arteriae vertebralis and encloses the vertebral artery (schematic drawing); macerated occiput and atlas of a 65-year-old woman

Figure 5 there are two ligamentous strands cranial to the vertebral artery that reach the osseous appendage.

The macerated specimen of that case (see Figure 1) shows that the osseous process consists of coarse spongious bone and is only covered by a thin lamella of compact bone. The basis of this process, which measures a maximum of 4.8 mm at the widest point in caudal view (see Figure 2b), is located laterally to the posterior quarter of the occipital condyle wherein the posterior half of the process has a triangular tip (see Figure 2b). The total length of this structure is 6.5 mm, measured from the base of the process to the most dorsal point at the tip.

In addition to these findings, the first cervical vertebra has further peculiarities, which we could observe most notably on the contralateral (=right) side: The dorsal arch of the atlas showed a bony bridging of the vertebral artery, which is thus surrounded by bone in the sulcus arteriae vertebralis. This anomaly corresponds to the well-known Ponticulus atlantis posterior, or clinically speaking Ponticulus posticus respectively. Beneath this bony covering of the vertebral artery there was an anomalous upper joint surface on the right side of the atlas which seemed to be separated incompletely into an anterior and a posterior compartment (Facies articularis superior bipartita atlantis).

3.3.2 | Case 2

The second case is the external skullbase of an 89-year-old man with a Processus condylicus posterior on the right side (see Figure 2a). The topographical situation of the osseous and ligamentous tissue is identical to the previous case. The same applies to the consistency of the bony preparation with its thin compacta and large-pored cancellous bone.

This process, measuring at its basis 6.0 mm in lateral alignment, has a full length of 6.0 mm in anterior-posterior orientation from base to posterior apex. In contrast to the first case, which appears triangular like an arrowhead (Figure 2b), the structure presented here has a rather clumsy shape that is remotely reminiscent of a hook (Figure 2a).

In addition to this bone clasp there is a raised portion on both sides of the Foramen magnum, but with accentuation on the right side, laterally of the occipital condyles, which in its shape is reminiscent of the transverse process of the atlas. However, this prominence is part of the lateral portion of the occipital bone and is firmly fused to it (see Figure 2a).

3.4 | Ponticulus atlantis posterior

The Ponticulus atlantis posterior, an osseous bridge, that spans the vertebral artery in its course over the lateral posterior arch of the atlas (see case 1 above and Figure 6), was found in the present study material on a total of 11 of 50 preparations (22%), whereby 2 of these 11 cases showed a bilateral manifestation (4%). However, this bony bridge may also be only gradually developed, so that an anterior bone spinula at the dorsal aspect of the superior articular process and/or a posterior spinula at the posterior arch of the atlas can be observed, bridging only parts of the vertebral artery (resulting in a so-called Spinula anterior/posterior, see Figure 7). Such cases of an incomplete arch were observed in a total of nine specimens (18%).

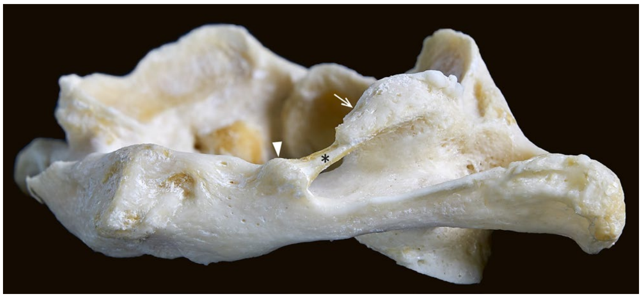

FIGURE 7 Posterolateral view on posterior and transverse portion of a first cervical vertebra: Fibrous, non-osseous strand (*) spans the right osseous grove of the posterior atlas arch; osseous spinulae form an incomplete bridging of the Sulcus arteriae vertebralis (Spinula anterior (small arrow), Spinula posterior (arrowhead)); macerated atlas of an 82-year-old man, stored in ethanol

FIGURE 8 Posterolateral view on right condylar fossa: Bony strip (arrowhead) points towards to jugular process; macerated occiput of a 73-year-old man

TABLE 1 Summary of all Proatlas-manifestations found by examining 50 skull bases and first cervical vertebrae

Proatlas-manifestation	*n*	%
Canalis nervi hypoglossi bipartitus	11	22
Processus basilaris	1	2
Labia foraminis magni posteriora	8	16
Processus condylicus posterior	2	4
Tuberculum paracondylicum	3	6
Processus epitransversus	1	2
Ponticulus atlantis posterior	11	22
Ponticulus atlantis lateralis	1	2
Facies articularis superior bipartita atlantis	9	18

Furthermore, at the specimen of an 82-year-old man it could be explicitly shown that the vertebral artery can be bridged not only by a bony but also by a fibrous structure (see Figure 7). The topography of this ligament is homologous to its bony counterpart described above. In the present case, in addition to the fibrous structure, we documented an anterior and posterior spinula (see above).

In summary, 20 of 50 specimens (40%) showed bony variations that represent a Ponticulus atlantis posterior or a gradual expression of such a ponticle in the sense of a Spinula anterior or posterior.

3.5 | Further osseous findings

Another case showed a fine bone spur dorsally of the right occipital condyle, which is located at the dorsal insertion site of the posterior condylar ligament (see Figure 8). This spur points anterolaterally towards the osseous rim lateral to the occipital condyles and is thus located exactly in the fibrous course of the above-mentioned ligament.

In addition to these special findings, which are directly associated with a potential manifestation of dorsal Proatlas-material, further bony manifestations of the Proatlas were found when looking through the macerated osseous preparations. Based on the manifestations listed in Prescher (1997), the anatomical variants found were classified as listed in Table 1.

4 | DISCUSSION

This dissection series showed that a fibrous strand connecting the posteromedial margin of the foramen magnum and the jugular process lateral to the occipital condyle of the human outer skullbase was present at 49 of 50 human craniovertebral junctions (98%). In addition, it was shown that ossicles can be found in this ligament, which came apparent in nine cases (18%). We found an osseous process, that can be classified as a Processus condylicus posterior, in at least two skullbases (2%), a rare manifestation of the human occipital bone.

The human atlanto-occipital articulation is a well-studied joint in the transition of the skull to the cervical vertebral column. Fundamental investigations into the mechanics and separate structures of this joint were summarized by Rudolf Fick in 1904. In this context, Fick also emphasized the role of a structure that reinforces the joint capsule of this joint from the dorsal side: Ligamentum occipitale accessorium posterius or posterior oblique occipito-atlantal ligament (synonyms at Fick, 1904). This ligament extends from the transverse process of the atlas to the retrocondylar region dorsal of the condylar fossa. The posterior condylar ligament examined in this study therefore extends one level higher with the same insertion from retrocondylar to the jugular process. Thus, the posterior condylar ligament can be understood as a cranial continuation of the posterior reinforcing ligament and due to its high prevalence as a regular part of the atlanto-occipital joint. The assumption of

Luschka, who already mentioned the posterior condylar ligament in 1862 though not naming it, that this ligament serves to protect the condylar emissary vein which protrudes below the ligament, must be contradicted at this point: Finally, in seven cases (14%) it has been observed how this vein passes through the ligament what is clearly contrary to a protective function. In addition, it is known that in 53.4% the condylar foramen can be completely absent by closure on one or on both sides (Boyd, 1930), so that a condylar emissary vein is missing in these cases. This is also in contrast to the function proposed by Luschka since we assume, based on the regular occurrence shown in this study, that a posterior condylar ligament can still be found in these cases.

Rather, we see a common function of posterior condylar ligament and posterior oblique occipito-atlantal ligament as a complex, ergo the support of the joint or joint capsule from posterior. This complex of ligamentous attachments posteromedial to the occipital condyles has been also noted by Cave (1933–34) and was described in more detail by Humphrey (1858) and Morris (1879). Humphrey describes another ligament in addition to the posterior condylar ligament and Fick's Ligamentum occipitale accessorium posterius (see above). Humphrey's ligament extends from the posterior margin of the Foramen occipitale magnum to the posterior aspect of the superior articular process of the atlas and is also called unfortunately the posterior oblique ligament as well. Humphrey attributes a major role in joint stability to this structure, in part because of a poor mechanical stability of the posterior atlanto-occipital membrane (Humphrey, 1858). Morris (1879) also gives a detailed description of the ligamentous structures and emphasizes a stable fibrous tract of thick fibers posterior to the joint capsule. According to Morris, these fibers serve to control the flexion of the head on the cervical spine.

In Figure 5, the remains of Fick's Ligamentum occipitale accessorium posterius are marked with an asterisk (*). The ligamentous part that runs to the transverse process of the atlas has been removed in favor of the depiction of the vertebral artery. The fact that such corresponding structures can also be found on the front side of the atlantooccipital joint was also shown by Fick (1904).

With regard to the assumed supporting function of the posterior condylar ligament, it is not surprising to find fibers connecting the ligament to the ipsilateral joint capsule in 8% of the studied specimens. Furthermore, Cruveilhier (1837) described fiber complexes which can be found in this region ('Ligaments occipito-atloïdiens latéraux') and forming fibrous complexes with radiating fibres at the jugular process.

Thus, three clearly defined ligaments that can be delineated from one another and that potentially stabilize the joint capsule posteriorly can be identified:

1. Posterior condylar ligament, between posterior margin of the Foramen magnum and jugular process;
2. Ligamentum occipitale accessorium posterius (Fick, 1904), between posterior margin of the Foramen magnum and the transverse process of the atlas (CAVE: This is not identical to the following ligament despite partially identical designation; therefore, the Latin form is used here);
3. Posterior oblique occipito-atlantal ligament (Humphrey, 1858), between the posterior margin of the Foramen magnum and the posterior aspect of the superior articular process of the atlas.

Further we could observe in nine (18%) of 50 cases ossicles, lying in the posterior condylar ligament (see Figure 4). Ossicles at the laterodorsal margin of the foramen magnum, embedded in fibrous tissue, have been also described before (Misch, 1905; Schumacher, 1907; Tischendorf, 1952; Trolard, 1892). Considering the long history of studying the variations at the craniocervical junction in the morphological disciplines, it may at first seem surprising that these free ossicles were not noticed more often. At this point it should be noted that these ossicles usually get lost during maceration, so that as a result, free ossicles such as those found in this study have simply rarely been seen although these are relatively common.

While Trolard (1892) did not relate his findings to possible Proatlas-manifestations, Schumacher (1907) and Tischendorf (1952) interpreted the free bone clasps as the posterior arches of an accessory vertebra between the atlas and occiput as we do. We see the detachment of this material from the occiput resulting in the ossicles observed here; the complete assimilation of this material, which is the rule, results in a regular morphology of the margin of the foramen magnum. If this embryological material is incorporated incompletely, a phenomenon known as Labia foraminis magni posteriora can be observed (see Table 1 and Figure 9). Schumacher (1907) goes even further and interprets the ligamentous tissue in which the ossicles are embedded as Proatlas-tissue as well. He states that in his

FIGURE 9 Caudal view on skullbase around the Foramen magnum; the arrowheads mark osseous bulges at the posterior margin of the Foramen magnum: Labia foraminis magni posteriora; macerated specimen of a 75-year-old woman

sample the rectus capitis lateralis muscle, which is an intertransverse muscle connecting the transverse processes of adjacent vertebrae, has its cranial insertion not only at the occiput but also at this ligament. According to Schumacher, this is a further indication that the ligament including the ossicles derive from the material of a vertebra between the atlas and the occiput.

The theory that the found free ossicles are sesamoid bones was rejected under consideration of the extensive work of Pfitzner on this topic (Pfitzner, 1892). Also contrary to this is the fact that this is a region in which, considering the previous findings (see above) on the manifestation of Proatlas-material, free ossicles are to be expected (Hayek, 1927). Thus, in contrast to the absence of these ossicles, they do not represent an unexpected event.

Other ossicles, that have already been found at the transition of the squamous to the lateral portion of the occiput, shall not be mixed up with the free ossicles found in this study. An example is given by Staurenghi (1900): Ossicula exoccipito-supraoccipitalia ("ossicini exoccipito-sovraoccipitali") which can be found as Ossa Wormiana between exoccipital and supraoccipital portions of the occiput. These ossicles, located in cranial sutures, are not to be classified as part of a Proatlas-manifestation.

In summary, we interpret the free ossicles found as a gradual expression of the posterior arch of the Proatlas respectively as a fail of regression of this material; further on there is evidence that the posterior condylar ligament is also derived from that vertebra.

The manifestation of a Processus condylicus posterior has been found in two cases (4%). In comparison with the small number of cases reported in literature, this prevalence does not appear to be representive. However, the aim of the present study was not to establish prevalence data, but rather to elaborate further details of this bony supernumerary structure and its relationship to the posterior condylar ligament. These details are mainly provided by the preparation of the ligaments in the two cases where the anomaly was found. Initial attempts were made to acquire sufficiently high-resolution CT images of the process and also of the ossicles, but these attempts were not followed by satisfactory success. As explained in the beginning, we assumed that the tissue of origin of the ligament is identical to the tissue the bony process derives from. This assumption is confirmed by the fact that in both cases 1 and 2 the ventral insertion is located at the dorsal pole of the process (see Figure 5). We see here an incomplete ossification that results in a bony clasp in the anterior region and fibrous connective tissue in the posterior region. According to the position and topography of the ligament and the potentially developing appendages, we clearly agree with Hayek (1927) in his view that the Processus condylicus posterior derives from dorsal arch material of the Proatlas. Further Bystrow (1931) clearly defines the formation of the Processus condylicus posterior as "Manifestatio arcus posterioris proatlantis". This becomes even more apparent when looking at bilateral expressions of this variant (see Bystrow, 1931: figure 9b, Prescher, 1997: figure 9): the osseous processes appear like the roots of a posterior vertebral arch, not unlike those of the posterior arch of the atlas.

Further evidence of this assumption provides us another interesting and well researched manifestation of the Proatlas: The Ponticulus atlantis posterior. The bony bridging of the vertebral artery in the sulcus arteriae vertebralis is a common osseous anomaly, the prevalence of which is given as 9.1% in a meta-analysis by Pekala et al., (2017). The amount of studies carried out and the literature written on this subject is immense, so that we only refer to some fundamental works at this point (Hauser & de Stefano, 1989; Hayek, 1927; Kimmerle, 1930; Pekala et al., 2017, 2018; Prescher, 1997; Torklus & Gehle, 1975). Due to its topographic relation to the vertebral artery (Figure 6), especially the Ponticulus atlantis posterior (but also other Proatlas-manifestations) have been identified as a risk factor for the development for manifold disorders: headache, migraine cervicale, neck pain, shoulder pain, dissection of vertebral artery and other, mostly neurological, symptoms. The common pathophysiological basis of these symptoms seems to be the stenosis of the vertebral artery and/or irritation of the sympathetic nerve plexus encompassing the vertebral artery (Münchow & Mucha, 1965; Pekala et al., 2018; Torklus & Gehle, 1975). From morphological perspective, venous outflow obstruction with clinical relevance is also quite theoretically conceivable due to the topographical location of the ligament, process and ossicles found. That the venous drainage of the suboccipital venous plexus can be altered in cases of osseous variation of the atlas, has been shown and discussed by Le Minor (1997) in cases of a Foramen retrotransversum atlantis.

Comparing the Processus condylicus posterior (Figure 1) with the Ponticulus atlantis posterior (Figure 6) regarding their topographical conditions, it becomes clear that similar clinical symptoms are also conceivable in cases of a Processus condylicus posterior: both are kind of bridging the vertebral artery, accompanied by all conceivable pathophysiological processes described above.

Another interesting aspect when looking at incomplete manifestations of a posterior ponticle is the fact that the vertebral artery can be bridged by ligamentous tissue as depicted in Figure 7. The anterior and posterior spinulae work as anterior and posterior insertion points. This behavior is comparable to the concept that the posterior condylar ligament forms a precursor structure for the bony Processus condylicus posterior and similar formations. Further on the comparison of Processus condylicus posterior and Ponticulus atlantis posterior, whoms origin in dorsal Proatlas-material is generally accepted, give rise to this hypothesis: The topography of the ligament and especially the osseous process is almost identical to the Ponticulus atlantis posterior. In addition to that it is notable that in the cases of a Processus condylicus posterior-manifestation an ipsilateral Ponticulus atlantis posterior has not been oberserved yet. We interpret this behavior in the way that osseous material of the dorsal Proatlas-arch can either form a bony bridge on the atlas (Ponticulus atlantis posterior) or a bony spur dorsolateral to the Foramen magnum (Processus condylicus posterior). A close relationship between the pontic and the process is recognizable and traceable to the same origin: the neural arch of the Proatlas.

As we see in the manifestation of the Processus condylicus posterior a fail to regression of the dorsal Proatlas-material, it is essential to us to establish a typology that shows that different stages of regression give rise to different manifestations. In the following we will present such a typology as can be seen in Figure 10, based on the findings of this study:

Type I: The Proatlas-material, which forms the basis for the posterior vertebral arch, was completely receded, so that the posterior condylar ligament could not develop. In our dissection series only one specimen showed this total regression on one side of the foramen magnum.

Type II: In this case, material of the posterior arch persists so that the posterior condylar ligament will be formed. According to the results of this study, this corresponds to the most common type.

Type III: In this case, tissue persists which further on differentiates into bone, but is not in continuity with the osseous outer skullbase. Thus, such free ossicles are formed in the posterior condylar ligament, the shape tends to be elongated. We assume that the prevalence of this type is much higher than previously supposed in literature, since using the most common method for gaining osseous specimen (water maceration) will mostly lead to the loss of these ossicles.

Type IV: This type has been divided into type IV–A and type IV–B: Type IV-A represents a persistence of osseous material, that forms in consequence a bony spur that is ventrally in connection with the laterocondylar region of the occiput: Processus condylicus posterior. This rare Proatlas-manifestation is the ventral insertion point of the posterior condylar ligament. Type IV–B on the other hand is the formation of a bony process dorsal to the condylar fossa (see Figure 8) and is therefore the posterior insertion point of the ligament.

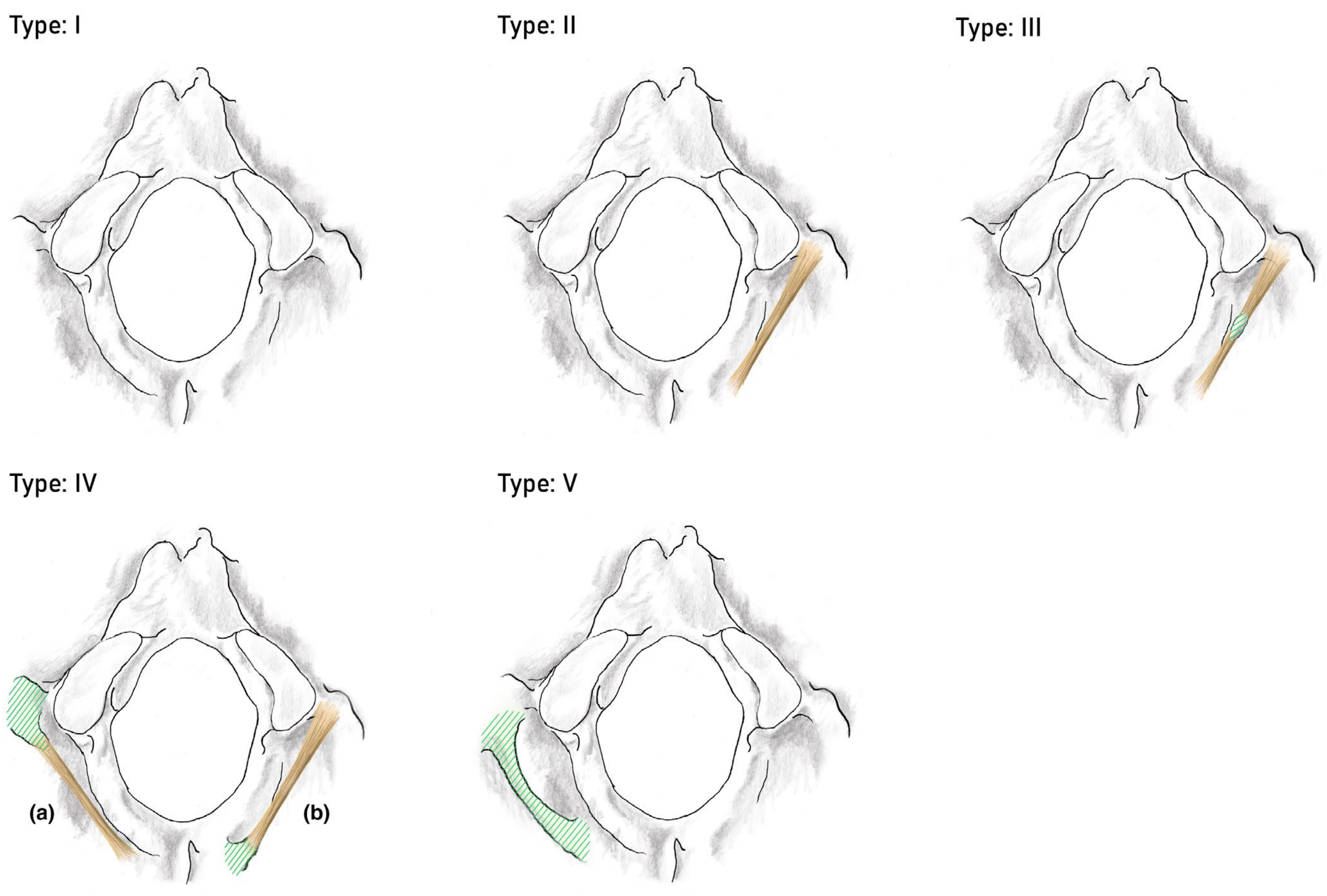

FIGURE 10 Typology of the posterior condylar ligament and related structures deriving from it: Types I–V. For reasons of simplification, the variant is shown in each case on the left lateral aspect of the foramen magnum (=right in the figure); the only exception is type IV, in which type IV-A is shown on the right lateral aspect of the foramen magnum (=left in the figure) and type IV-B on the left lateral aspect of the foramen magnum (=right in the figure). The bony derivatives of the posterior Proatlas arch, which derive from the posterior condylar ligament have been highlighted in color; the vertical axis in the image corresponds to the anterioposterior direction: the top of the figure points anteriorly. Type I: total failure of formation of ligamentous or osseous derivatives due to total regression; Type II: the most common type with formation of the posterior condylar ligament; Type III: a free ossicle can be found within the course of the posterior condylar ligament; Type IV-A: at the anterior laterocondylar insertion point of the posterior condylar ligament, there is a bony process that is clearly directed occipitally: Processus condylicus posterior; Type IV-B: a similar structure, but much less prominent, can be found at the posterior insertion of the ligament in this type; Type V: this type represents a bony arch over the condylar fossa connecting the anterior and posterior insertion points of the ligament; this is only a hypothetical structure that can be expected to be found in further examination of human occipital bones based on previous findings. Misch (1905) has mentioned such a structure on a specimen, but a detailed description in literature is still missing

Type V: In consideration of the not yet found but conceivable possibility that a complete osseous clasp bridging the condylar fossa can manifest, type V was included in this typology. The only indication that such a structure was observed was found in Misch (1905), but the description of this finding is rather concise and has not been depicted graphically. The fact that a finding of this type has never been described in detail to our knowledge does not exclude the possibility of existence of this type.

This typology depicts the hypothesis that the Processus condylicus posterior and related structures derive from the posterior condylar ligament. This hypothesis can finally be supported by phenomenological observations and well-founded assumptions mentioned above. This study represents a continuation of a previous study (Prescher, 1997) and confirms the phenomenological statements made at that time about the bony process. Unfortunately, a bilateral expression of this variety could not be found this time.

5 | CONCLUSIONS

The posterior condylar ligament is part of the regular anatomy of the atlanto-occipital joint. This structure derives most likely from the posterior Proatlas-arch. This hypothesis is confirmed by previous investigations as well as by the present study. Further on there is evidence reported in literature that the most ventral part of the ligament derives from material of the transverse process of the Proatlas. The formation of bony elements can lead to various structures such as free ossicles or osseous spurs like the Processus condylicus posterior. A typology of the possible manifestations has been proposed here (Types I to V). Depending on the degree of manifestation, various pathologies of the sympathetic vertebral plexus, vertebral artery and suboccipital venous plexus are conceivable based on the topographic conditions of the Processus condylicus posterior. Subsequent computed tomographic studies must, first, depict accurate imaging of the structures that derive from the posterior condylar ligament and, second, use extensive clinical data to clarify the clinical significance of the bony process and related structures.

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CONFLICT OF INTEREST

No conflict of interest has been declared by the authors.

AUTHOR CONTRIBUTIONS

Michael Wolf-Vollenbröker contributed to formal analysis; investigation (leading); visualization; writing – original draft preparation. **Andreas Prescher contributed to** conceptualization; investigation (supporting); project administration; resources; supervision; writing – correction of the manuscript.

DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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