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REVIEW

Morphological and functional anatomy of the trigeminal triangular plexus as an anatomical entity: a systematic review

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Abstract

Purpose The sensory trigeminal nerve in the trigeminal cave of Meckel—which is an individualized lodge—is classically segmented into two parts: the trigeminal ganglion (TG) and the triangular plexus (TP). The TP has been defined as the portion of the trigeminal nerve from the posterior margin of the TG to the path over the upper ridge of the petrous bone. Due to its relatively unrecognized status, its morphological and functional anatomy has been reviewed by the authors through a PRISMA systematic review of the literature.

Methods The authors have carried out a systematic review of the TP according to the PRISMA model with various bibliographical bases. Before 1947: Medic @ Library (BIU Santé Paris, 2017); Index-Catalog of the Library of the Surgeon-General's Office (US National Library of Medicine, 2017); Gallica (French National Library, 2017). After 1947: PUBMED, PubMed Central and MEDLINE.

Results 56 articles were retained for full-text examination, of which 23 were chosen and included. The TP was described as having a triangular shape (30.2%), a plexual organization (97.4%) with sensory-, motor- and sympathetic-anastomoses (96.7%) that, however, respect the somatotopic trigeminal distribution (93.3%). The direct electrical stimulation of the root at the level of the TP (during radiofrequency-thermorhizotomy procedures) confirmed a clear-cut somatotopy.

Conclusion An understanding of both the morphological and the functional anatomy of the triangular plexus can contribute to accuracy and safety on the surgeries performed for trigeminal neuralgia and tumor removal inside the trigeminal cave.

Keywords Trigeminal nerve · Anatomy · Triangular plexus · Trigeminal neuralgia · Systematic review (PRISMA) · Meckel cave tumors

Introduction

The trigeminal nerve (TGN) is the largest cranial nerve converging to the ventral upper surface of the pons, with a large sensory and a smaller, rostral and medial motor component. The TGN is made up of three nerves which converge towards the trigeminal ganglion. They are responsible for the sensation of the face. The ophthalmic nerve (V1) enters the cranial cavity from the orbit via the superior orbital fissure and runs in the lateral wall of the cavernous sinus. The maxillary nerve (V2) penetrates the skull base via the foramen rotundum. The mandibular nerve (V3) becomes endocranial through the foramen ovale. Contrariwise we find the motor fibers responsible for masticatory function.

Then, the TGN extends from the trigeminal cave (TC), which is located in the middle fossa, to the cerebellopontine cistern in the posterior fossa through the porus trigeminus [13, 26]. The TC is a dural and arachnoid pocket coming

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from an evagination of the cerebellopontine cistern where the TGN rootlets are disposed like *a hand in a glove* [7, 29] and containing inside the trigeminal cistern cerebrospinal fluid. The TGN in the TC is segmented into two parts: the trigeminal ganglion (TG) and the triangular plexus (TP) (Fig. 1). The TP was historically described by Prochaska in 1779 as "Quintum par plurimos numerat funiculos a sua origine usque ad ganglion semilunare non omnes plane ejudem crassitiei, in quibus mutuae conjunctiones at-que separationes valde frequentes sunt" (Fig. 2) [32]; then by Krause in 1896 who named the major crossing bundles in the dorsal root of the TGN "triangular plexus"[20]. According to Dandy [3] and Jannetta [14], the TP corresponds to the retrogasserian portion of the TGN that courses from the TG to the superior petrous ridge. Contrary to the TG with its three divisions (V1, V2, V3) and to the TGN cisternal portion in the cerebellopontine angle with its trigeminal root entry zone (TREZ), the anatomy of the TP has been relatively ignored per se with the exception of a few important anatomical dissections and electrophysiological studies.

We consider it is important to pay special attention to the anatomy of this particular segment, as this may contribute to the accuracy and safety of surgeries such as trigeminal neuralgias procedures and microsurgical removal of the tumors

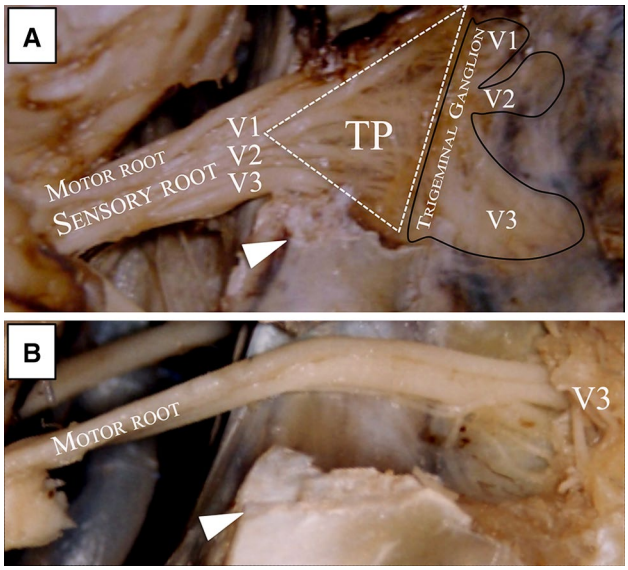

Fig. 1 Cadaver dissection of (right) trigeminal nerve within trigeminal cave, after the removal of its roof, in superior view (photography). **a** The triangular plexus (TP, dashed triangle) is exposed from posterior margin of the trigeminal ganglion to the crossing of root over the upper petrous ridge (white arrowhead) posteriorly. **b** After resection of the trigeminal sensory root and trigeminal ganglion, one can see the course of the trigeminal motor root from the cerebellopontine cistern to its penetration into the foramen ovale, together with the mandibular nerve (V3). Courtesy of the anatomical laboratory of Lyon university. Specimen dissected by E. Wydh, P. Mertens and M. Sindou

located inside the TC. The goal of this review was to collect knowledge on the TP from the literature, using standardized *terminologia anatomica* nomenclature, with the purpose of pointing out its implications in clinical and surgical fields.

Study design

Preferred reporting items for systematic reviews and meta-analyses (PRISMA) is an evidence-based minimum set of items for systematic reviews and meta-analyses. PRISMA focuses on the reporting of reviews evaluating randomized trials, but can also be used as a basis for reporting systematic reviews of other types of research [33].

The following bibliographic databases were examined

Literature before 1946 Medic@ Library (BIU Santé Paris, 2017); Index-Catalog of the Library of the Surgeon-General's Office (US National Library of Medicine, 2017); Gallica (Bibliothèque Nationale Française, 2017).

Literature published since 1946 was accessed via internet-wide and database searches of both public and academic literature (that is, PubMed, PubMed Central and MEDLINE).

Keywords

The TP (also named 'pars triangularis') is a term used since 1896 [20] but rarely defined as such, and, therefore, not yet studied specifically in the literature, so that the PRISMA review keywords had to be numerous as shown in Fig. 3.

Selection criteria

Inclusion criteria

Articles of interest must reported the use of the study method, the precise description of TGN segmentation, its anatomy in the trigeminal cave especially in the retrogasserian part, its relationship with the trigeminal cistern, its eventual somatotopic organization and rootlets anastomosis.

Exclusion criteria

The research tools provided a first set of sources that were more or less relevant and, therefore, required additional sorting. Excluding criteria were as follows: (1) study which did not focus on the TGN in the TC (e.g., TREZ, brainstem or cavernous sinus studies), (2) duplicate, and (3) review article.

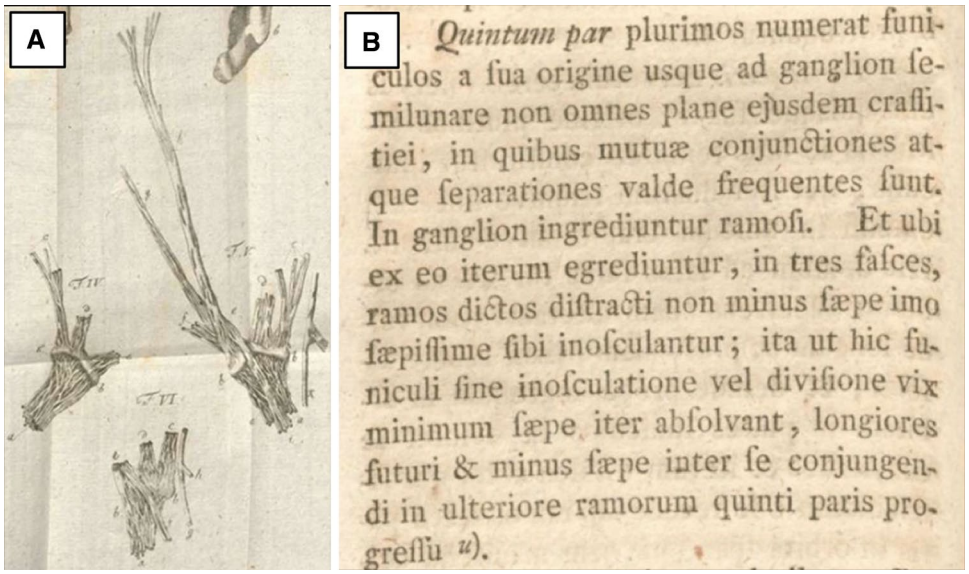

Fig. 2 First description of trigeminal nerve triangular plexus. **a** Illustration of the structure of the fifth cranial nerve with India ink from Prochaska (1778). Note that the plexual distribution of the triangular plexus is particularly well detailed. **b** Description of Prochaska in structura nervorum: "The fifth pair has many fibers, from its origin to a semilunar ganglion not all exactly the same thickness, which are reciprocal links and very frequent separations"(traduction from Latin). Source gallica.bnf.fr/Bibliothèque nationale de France.

Final sample

After abstract examination based on the inclusion and exclusion criteria, articles were retained for full-text examination, of which some articles were chosen to be included in this review.

Results

Part I: prisma review

After abstract examination based on the inclusion and exclusion criteria, 56 articles were retained for full-text examination, of which 23 were chosen to be included in this review.

Figure 4 is a PRISMA flow diagram, which illustrates the number of articles at each data acquisition level, the number of excluded articles and the reasons for exclusion [33] (Fig. 4).

Part II: knowledge from review

Our review showed that the TGN in the TC could be divided in two segments: the TG anteriorly and the TP posteriorly (Fig. 1; Table 1). We classified the main descriptions of each segment for the plexual distribution, the presence of anastomoses and the somatotopy.

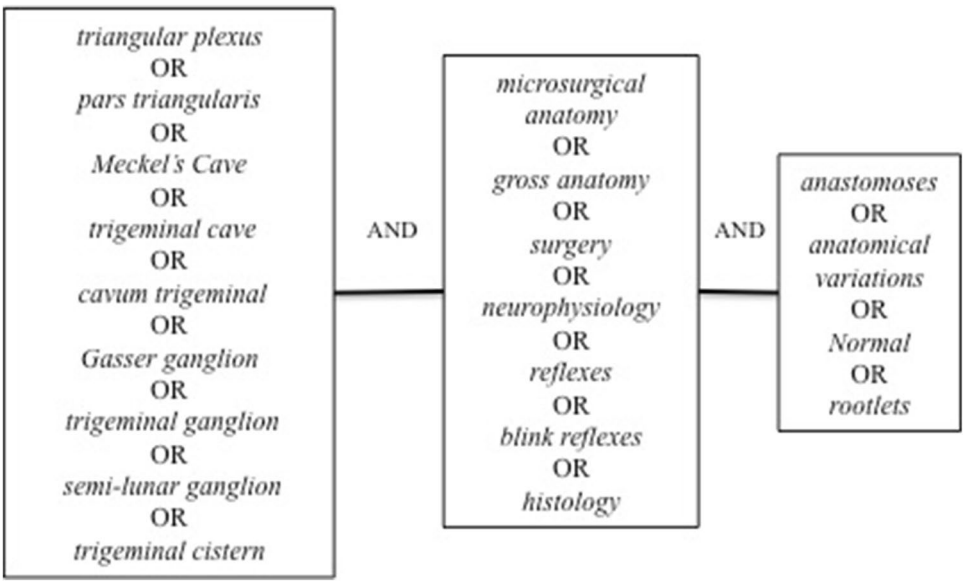

Fig. 3 Chart showing authors' research strategy and terms

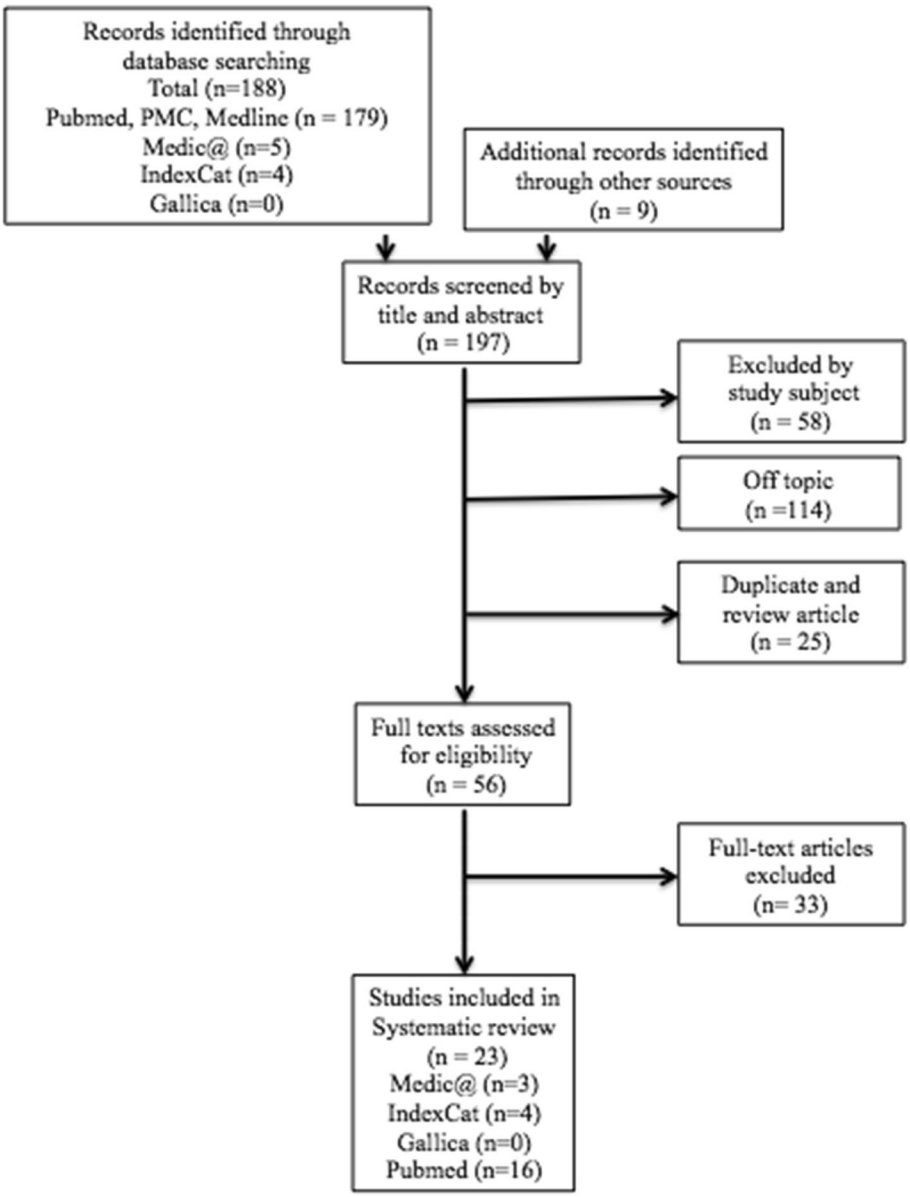

Fig. 4 PRISMA diagram showing the flow of information through the different phases of the systematic review

The triangular plexus

Anatomical observations Reviewed studies included surgical anatomy (2992 surgical cases reported) and formaldehyde preserved specimens (216 specimens), from which 46 (21.3%) were latex injected (Table 2).

The TP was recognized as an anatomical entity in 83.2% (Table 3), whereas the other segments of the TGN—that is the V1, V2 and V3 nerves, the TG and the TGN root—were described by all authors (Table 1). Whichever the segmentations of the TGN, most authors depicted TGN main characteristics as posterior to the TG. The nerve in this portion was described as having a plexual distribution (97.4%) with anastomoses (96.7%); that respected the somatotopic distribution, however (93.3%) (Tables 3, 4). Authors depicted that the TP could be characterized by a triangular form in only one-third of the publications (30.2%). Besides, the motor component of the TGN was described inferomedial to the TP in 80.7% and ventral in 77.2% before reaching exit to the foramen ovale. Concerning the arachnoid sheath, the trigeminal cistern was described coming from the prepontine cistern and terminating at the TP level in 97.3% (Table 5).

Contrary to the TP, the anatomical description of the TG was more consensual. The TG was recognized as an anatomical entity in 100% (Table 6). Most authors depicted five TG characteristics that were useful: the nerve in this portion did not have a plexual distribution (0%) without anastomoses (0%) nor arachnoid sheet (0%) and respect a somatotopic

Table 1 Segmentation of trigeminal nerve

Trigeminal nerve segmentation	Part V1–V3	Trigeminal ganglion	Triangular plexus	Root	NA	Number of sides studied
Meckel 1748 [24]	1	1	0	1	0	1
Prochaska 1779 [29]	1	1	1	1	0	1
Krause 1896 [19]	1	1	1	1	0	1
Frazier 1925 [7]	1	1	1	1	0	1
Van Nouhys 1929 [42]	28	28	28	28	0	28
Kirschner 1933 [18]	1	1	1	1	0	1
Henderson 1965 [10]	80	80	80	80	650	730
Jannetta 1967 [13]	56	56	56	56	0	56
Gudmundsson and Rhoton 1971 [9]	50	50	50	50	0	50
Sweet 1974 [36]	353	353	0	353	0	353
Sindou, Keravel 1979 [33]	200	200	200	200	0	200
Kawamura 1988 [16]	6	6	6	6	0	6
Karol 1991 [15]	9	9	9	9	0	9
Sindou 1994 [32]	NA	NA	NA	NA	350	350
Sindou 1999 [35]	1260	1260	1260	1260	0	1260
Uryvaev 2008 [41]	78	78	78	78	0	78
Tatli 2008 [37]	100	100	100	100	0	100
Leston 2009 [21]	1	1	1	1	0	1
Alvernia 2009 [1]	4	4	4	4	0	4
Sindou 2010 [31]	NA	NA	NA	NA	NA	NA
Peris-Celda 2013 [27]	36	36	36	36	0	36
Joo, 2014 [14]	10	10	0	10	0	10
Terrier 2018 [38]	22	22	NA	22	0	22
Total	2298 (100%)	2298 (100%)	1912 (83.2%)	2298 (100%)	1000	3298

distribution (93.3%). Finally, its shape was described semilunar. Note that the motor TGN was ventral to the TG to reach the foramen ovale (100%).

Histological studies Concerning the histological studies of the TP, reports are scarce. Only two studies using a histological method to assess the histological properties of the TP were found by our systematic review (Table 7). Histological techniques included Schiff stained and Christensen method (66.4%), or frozen histological section (33.6%). In Uryvaev et al. study, TP contained bundles of nerve fibers of diameter up to 100–150 µm, especially located in the superfical TP part. These fibers were wrapped in an arachnoid covering which corresponded to the trigeminal cistern [44]. The authors depicted a "chaotic" distribution without impact on the somatotopy. These authors established that numerous "branches" (50–150 µm in diameter) arose directly from the TGN, more from the outer and less from the deep surface that provided innervation to the walls of the trigeminal cavity. No connecting branches with the internal peri-carotid plexus, the greater petrous nerve or any other nerve were seen. The authors assumed that the outer position of these branches as well as their finest caliber are suggestive of being the sources of innervation of the dura and arachnoid mater that constitute the outer part of the wall of the trigeminal cavity. Conversely, the branches of V1 and V2, which penetrate the cavernous sinus, would likely innervate its internal part, i.e., the one facing the brain.

The histological characteristics of the TP were not clearly explained in the literature [2, 31]. Most cell bodies of the somatosensory neurons are located in the trigeminal ganglion, whilst the bodies' cells for proprioception and stretch receptors in the masticatory muscles are located in the mesencephalic nucleus. Based on monkey's experiments studying histology after degeneration, Emmons and Rhoton proposed that the proprioceptive afferents from the masticatory muscles run through the motor root to enter the mesencephalic nucleus [4]. The cellular bodies of the sensory fibers (T cells) are grouped at the level of the semilunar TG. They send central (axonal) extensions on passing at the superior part of the pontocerebellar angle to the sensory nuclei of brainstem. Their peripheral (dendritic) extensions form the fibers of the three branches of the TGN.

Table 2 Anatomical study method of the trigeminal nerve

Anatomic method of study	Surgery	Formol	Plastination	Latex	Silicon	Number of sides studied
Meckel 1748 [24]	NA	NA	NA	NA	NA	1
Prochaska 1779 [29]	0	NA	NA	NA	NA	1
Krause 1896 [19]	NA	NA	NA	NA	NA	1
Frazier 1925 [7]	0	1	0	0	0	1
Van Nouhys 1929 [42]	0	28	0	0	0	28
Kirschner 1933 [18]	1	0	0	0	0	1
Henderson 1965 [10]	650	80	0	0	0	730
Jannetta 1967 [13]	56	56	0	0	0	56
Gudmundsson and Rhoton 1971 [9]	0	0	0	0	0	50
Sweet 1974 [36]	353	0	0	0	0	353
Sindou, Keravel 1979 [33]	200	0	0	0	0	200
Kawamura 1988 [16]	0	0	0	0	0	6
Karol 1991 [15]	0	0	0	0	0	9
Sindou 1994 [32]	350	0	0	0	0	350
Sindou 1999 [35]	1260	0	0	0	0	1260
Uryvaev 2008 [41]	0	0	0	0	0	100
Tatli 2008 [37]	100	0	0	0	0	78
Leston 2009 [21]	0	1	0	0	0	1
Alvernia 2009 [1]	0	4	0	4	0	4
Sindou 2010 [31]	NA	NA	NA	NA	NA	NA
Peris-Celda 2013 [27]	0	36	0	36	0	36
Joo, 2014 [14]	0	10	0	10	0	10
Terrier 2018 [38]	22	0	0	0	0	22
Total	2992	216	0	46	0	3298

Neurophysiological explorations To advance knowledge on functional anatomy of the TGN, we could benefit from neurophysiological explorations of percutaneous procedures, especially Radiofrequency-thermorhizotomies (RF) of the TGN (Table 8). According to the original description of the RF method by Sweet and Wepsic, the procedure is based on the verification of the accurate place of the electrode by observation—the patient being awake—of the sensory responses (paresthesias) to direct stimulation of the TGN at 50 Hz [39]. Evoked paresthesias are currently located in the V3 division when the tip of the electrode is in the most lateral part of the TP; in the V1 division when in the most medial part; and in V2 division when the tip is located in between.

Performing Sweet's method, Sindou and Keravel found the same topographical distribution of the sensory responses [36]. By adding a stimulation mode at 5 Hz, they could observe (in approximately 50% of their patients) clinically observable synchronous twitches in orbicularis oculi, orbicularis oris or levator labii when electrode was, respectively, in superomedial, inferolateral or intermediate location [35, 37]. These phenomena—that revealed to be of localizing value [38]—were considered brainstem trigemino-facial reflexes.

The obtaining of the blink reflex elicited by direct stimulation of the root was also noticed during percutaneous glycerol injection procedures by Kawamura et al., who recommend this checking to confirm appropriate location of the needle in the TC [17]. In an attempt to enhance the accuracy of electrode localization during RF, Karol also used sensory and motor trigeminal-evoked potentials to direct stimulation of the root in complement of the clinical sensory responses [16].

The anatomical relationships of the triangular plexus

Access to the TP needs to consider direct anatomical relationships with its neighboring structures.

Anteriorly: the trigeminal ganglion The TG has a semilunar shape and presents: (1) a convex anterior edge where the three peripheral branches terminate; (2) a concave posterior margin from which the sensory rootlets emerge. Between their emergence of the TG and the upper ridge of the petrous bone, rootlets form a triangular blade, named "TP" because of anastomoses [18]. At the TP level, somatotopy of sensory fibers is almost as clear-cut as in the TG [10, 28, 40].

Table 3 Triangular plexus characteristics

Triangular plexus characteristics	Plexual distribution	Anastomoses	Triangular form	Posterior end in the prepontine cistern	Somatotopy	NA	Number of sides studied
Meckel 1748 [24]	NA	NA	NA	NA	NA	1	1
Prochaska 1779 [29]	1	1	1	NA	NA	0	1
Krause 1896 [19]	1	1	1	NA	1	0	1
Frazier 1925 [7]	1	1	1	0	NA	0	1
Van Nouhys 1929 [42]	8	8	28	NA	28	0	28
Kirschner 1933 [18]	NA	NA	NA	NA	NA	1	1
Henderson 1965 [10]	80	80	80	NA	80	650	730
Jannetta 1967 [13]	56	56	56	0	56	0	56
Gudmundsson and Rhoton 1971 [9]	50	50	NA	NA	50	0	50
Sweet 1974 [36]	NA	NA	NA	NA	NA	353	353
Sindou, Keravel 1979 [33]	200	200	200	0	200	0	200
Kawamura 1988 [16]	6	6	NA	NA	6	0	6
Karol 1991 [15]	NA	NA	NA	NA	9	0	9
Sindou 1994 [32]	NA	NA	NA	NA	NA	350	350
Sindou 1999 [35]	1260	1260	NA	NA	1260	0	1260
Uryvaev 2008 [41]	78	78	78	NA	NA	0	78
Tatli 2008 [37]	100	100	100	0	100	0	100
Leston 2009 [21]	1	1	1	0	1	0	1
Alvernia 2009 [1]	4	4	4	4	4	0	4
Sindou 2010 [31]	NA	NA	NA	NA	NA	–	NA
Peris-Celda 2013 [27]	36	NA	36	0	36	0	36
Joo, 2014 [14]	10	10	NA	10	10	0	10
Terrier 2018 [38]	NA	22	NA	NA	22	0	22
Total	1892 (97.4%)	1878 (96.7%)	586 (30.2%)	14 (0.7%)	1813 (93.3%)	1355	3298

However, Van Nouhys stressed the difficulty, to discriminate the precise somatotopy in the TP during dissections, due to the fact that the fibers do not run alongside, so that they could not be easily divided [45]. Anatomically, the TP–TG junction was imprecisely described in most studies. For Uryvaev et al., the junction corresponds histologically to the beginning of anastomotic fiber bundles, located in the anterior part of the trigeminal cistern, given that the arachnoid layer is adhesive to the TP [44].

Posteriorly: the TGN root At the rear of the upper petrous ridge, the TGN root located in the pontocerebellar cistern presents with a still relatively marked somatotopy, but obliquely organized. The (axonal) fibers corresponding to the mandibular territory (V3) predominate in an inferolateral position, the ophthalmic (V1) in a superomedial position and the maxillary (V2) in an intermediate location [10]. Further posteriorly, on penetrating the pons, the root undergoes a functional rearrangement with three distinct components: the pars minor (superomedial), with a motor function, the pars major (inferolateral), sensory and mostly thermoalgesic, and in between the two, the pars intermedia [41]. The sensory fibers tend to group at the juxtapontine level according to their destiny and, therefore, function [15]. The thermoalgesic fibers are placed in the pars major, to then follow the descending tract down to the spinal nucleus at the spinal cord–medullary junction. Also classically, the epicritic and proprioceptive fibers would transit in the pars intermedia to then reach the pontine nucleus [42].

The corneal reflex, which is the substratum of a protective autonomic and somatic function, including blinking and lacrimation, obeys to "nociceptive" mechanisms. Electrophysiological and histological studies have shown that cornea is innervated by A delta and C fibers [24, 27]. Some authors considered that corneal fibers run into the pars intermedia [5]. On the contrary, Terrier and al. assumed that all corneal fibers run along the dorsomedial third of the pars major, based on their surgical experience. This postulate explains the two-third pars major rhizotomy used by the senior author (S. Velut) in specific cases of trigeminal neuralgia [41]. Limiting the rhizotomy to the inferolateral two-thirds of the pars major would be the way to avoid corneal ulcer caused by sensory impairment.

Table 4 Somatotopy in the trigeminal ganglion

Trigeminal ganglion somatotopy	V1	V2	V3	Motor V3 ventral to TG and TP	Motor V3 infero-medial to sensitive V3	NA	Number of sides studied
Meckel 1748 [24]	1	1	1	NA	NA	0	1
Prochaska 1779 [29]	1	1	1	1	NA	0	1
Krause 1896 [19]	1	1	1	1	1	0	1
Frazier 1925 [7]	1	1	1	1	1	0	1
Van Nouhys 1929 [42]	28	28	28	28	28	0	28
Kirschner 1933 [18]	1	1	1	NA	NA	0	1
Henderson 1965 [10]	80	80	80	NA	80	650	730
Jannetta 1967 [13]	56	56	56	56	56	0	56
Gudmundsson and Rhoton 1971 [9]	50	50	50	50	50	0	50
Sweet 1974 [36]	353	353	353	NA	NA	0	353
Sindou, Keravel 1979 [33]	200	200	200	200	200	0	200
Kawamura 1988 [16]	6	6	6	NA	NA	0	6
Karol 1991 [15]	9	9	9	9	9	0	9
Sindou 1994 [32]	NA	NA	NA	NA	NA	350	350
Sindou 1999 [35]	1260	1260	1260	1260	1260	0	1260
Uryvaev 2008 [41]	78	78	78	NA	NA	0	78
Tatli 2008 [37]	100	100	100	100	100	0	100
Leston 2009 [21]	1	1	1	1	1	0	1
Alvernia 2009 [1]	4	4	4	4	4	0	4
Sindou 2010 [31]	NA	NA	NA	NA	NA	NA	NA
Peris-Celda 2013 [27]	36	36	36	36	36	0	36
Joo, 2014 [14]	10	10	10	10	10	0	10
Terrier 2018 [38]	NA	NA	NA	NA	NA	22	22
Total	2276 (100%)	2276 (100%)	2276 (100%)	1757 (77.2%)	1836 (80.7%)	1022	3298

Inferiorly: the motor root The proprioceptive and myotactic fibers of the TGN, the majority from the masticatory muscles, after having traveled in the pars minor, i.e., the motor root, form the mesencephalic tract and terminate into the mesencephalic nucleus. In 77.2% (1757 case reported), the motor root was depicted ventral (i.e, inferior) to the TP and TG, then in all cases (Table 4) inferomedial to the V3 when reaching the foramen ovale. Two authors depicted anastomotic branchlets between motor and sensitive root. Van Nouhys depicted in most cases some fiber bundles emerging from the lateral part of the TP (supposed to correspond to the V2 and V3 divisions) to join the motor root [45]. Joo et al. described anastomoses between the motor and sensory roots in 47 of the 50 nerves studied [15].

Superiorly: the trigeminal cistern In the cerebellopontine cistern, the TGN is located in its rostral portion; there, the arachnoid covering its dorsal surface is in continuity with the sheath lining of the rostral surface of the cerebellum, which constitutes the superior limit of the superior cerebellar cistern. In the TC, the nerve is surrounded by an arachnoid sheath up to the rostral border of the TP in the TC, thus limiting the trigeminal cistern [9, 21, 23, 25]. Noteworthy, in its superior cerebellar cisternal course the root is vascularized by small branches of the superior cerebellar artery. From our review, the trigeminal cistern surrounded the superior part of the TP in 97.3% and was not depicted ventrally in the TG.

Discussion

The triangular plexus has been defined as the immediate retrogasserian portion of the trigeminal system: it corresponds to the dorsal sensory rootlets between the semilunar TG and the cisternal portion of the root in the cerebellopontine angle. The TP constitutes to a certain extent an anatomical surgical entity linked to its location inside the TC and with morphological particularities: its triangular form and its plexual aspect together with a well-preserved somatotopic organization at the functional level.

Table 5 Trigeminal cistern characteristics

Cisternal TGN characteristics	Cisternal ventral termination before the TP	Cisternal ventral termination at the TP level	Cisternal ventral termination after the TP (in the TG)	Cisternal ventral termination after the TG	NA	Number of sides studied
Meckel 1748 [24]	NA	NA	NA	NA	1	1
Prochaska 1779 [29]	NA	NA	NA	NA	1	1
Krause 1896 [19]	NA	NA	NA	NA	1	1
Frazier 1925 [7]	NA	NA	NA	NA	1	1
Van Nouhys 1929 [42]	NA	NA	NA	NA	28	28
Kirschner 1933 [18]	NA	NA	NA	NA	1	1
Henderson 1965 [10]	NA	NA	NA	NA	730	730
Jannetta 1967 [13]	0	56	0	0	0	56
Gudmundsson and Rhoton 1971 [9]	NA	NA	NA	NA	50	50
Sweet 1974 [36]	NA	NA	NA	NA	353	353
Sindou, Keravel 1979 [33]	NA	NA	NA	NA	200	200
Kawamura 1988 [16]	NA	NA	NA	NA	6	6
Karol 1991 [15]	NA	NA	NA	NA	9	9
Sindou 1994 [32]	NA	NA	NA	NA	350	350
Sindou 1999 [35]	NA	NA	NA	NA	1260	1260
Uryvaev 2008 [41]	0	78	0	0	0	78
Tatli 2008 [37]	NA	NA	NA	NA	100	100
Leston 2009 [21]	0	1	0	0	0	1
Alvernia 2009 [1]	4	0	0	0	0	4
Sindou 2010 [31]	NA	NA	NA	NA	NA	NA
Peris-Celda 2013 [27]	NA	NA	NA	NA	36	36
Joo, 2014 [14]	0	10	0	0	0	10
Terrier 2018 [38]	NA	NA	NA	NA	22	22
Total	4 (2.7%)	145 (97.3%)	0	0	3149	3298

Somatotopy in the triangular plexus

The plexiform aspect of the TP and its functional implication remain debatable. For Rhoton's anatomical school, many anastomoses were observed between the sensory fibers of each division (V1–V3) posterior to the ganglion. But in studies, they described the TGN root in its globality and did not individualized the TP properly [10]. Furthermore, they did not conclude any specific role to these anastomoses.

In the TC, the sensitive and motor TGN roots are close. The motor root goes under the TP and the TG from medial to lateral and from back to front to become a satellite for V3, at the foramen ovale. Joo et al. described anastomoses between the motor and sensory rootlets in 47 of the 50 nerves studied [15]. In addition to the presence of aberrant sensory fibers emerging from the pons, they assumed that motor-to-sensory anastomoses might explain the preservation of some sensation subsequent to cisternal sensitive rhizotomy of the trigeminal nerve.

Regarding the connections between the TGN and the sympathetic nerve plexus, Uryvaev et al. depicted up to 5–10 fine branchlets running from the internal pericarotidian plexus to the posteroinferior surface of the TGN and branching in the walls of the cavernous sinus [44]. It is worth noting that these sympathetic connections were not seen in the TC itself but within the walls of the cavernous sinus, suggesting that the internal pericarotidian plexus passes alongside the trigeminal ganglion separated from it by the wall of the TC, as described by François et al. [7]. The absence of sympathetic branches between the TGN in the TC is one more anatomical argument to consider the TC as an independent dural entity, different from the perisellar compartment.

These authors found numerous contacts of the TGN with this sympathetic plexus along the ophtalmic V1 nerve in the cavernous sinus. The branching of the sympathetic plexus and ophtalmic nerve forms the tentorial nerve and the cavernous nerve plexus. This gives rise to terminal branches which pass into the superior orbital fissure, the other part passing inside the optic canal [44]. Moreover, Uryvaev et al. assume that the significant numbers of anastomotic branches are the sources of innervation of the TC dura of the trigeminal cistern. Meanwhile the branches of the V1 and V2 nerves, which penetrate into the lateral wall of the cavernous sinus, innervate the TC inner part and the basal

Table 6 Trigeminal Ganglion characteristics

Trigeminal ganglion characteristics	Plexual distribution	Anastomoses	Without arachnoid space	Somatotopy	NA	Number of sides studied
Meckel 1748 [24]	0	0	1	NA	0	1
Prochaska 1779 [29]	0	0	NA	NA	0	1
Krause 1896 [19]	0	0	0	1	0	1
Frazier 1925 [7]	0	0	1	1	0	1
Van Nouhys 1929 [42]	0	0	NA	28	0	28
Kirschner 1933 [18]	0	0	1	1	0	1
Henderson 1965 [10]	0	0	80	80	650	730
Jannetta 1967 [13]	0	0	56	56	0	56
Gudmundsson and Rhoton 1971 [9]	0	0	50	50	0	50
Sweet 1974 [36]	0	0	NA	353	0	353
Sindou, Keravel 1979 [33]	0	0	NA	200	0	200
Kawamura 1988 [16]	0	0	NA	6	0	6
Karol 1991 [15]	0	0	NA	9	0	9
Sindou 1994 [32]	NA	NA	NA	NA	350	350
Sindou 1999 [35]	0	0	NA	NA	0	1260
Uryvaev 2008 [41]	0	0	NA	78	0	78
Tatli 2008 [37]	0	0	100	100	0	100
Leston 2009 [21]	0	0	1	1	0	1
Alvernia 2009 [1]	0	0	4	4	0	4
Sindou 2010 [31]	NA	NA	NA	NA	NA	NA
Peris-Celda 2013 [27]	0	0	36	36	0	36
Joo, 2014 [14]	0	0	10	10	0	10
Terrier 2018 [38]	0	0	22	22	0	22
Total	0	0	362 (15.8%)	1036 (100%)	1000	3298

arachnoid facing the brain. The clinical significance of these anastomoses could be found in the skull base dural and arachnoid innervations investigated in awake brain surgery procedures [6].

Surgical implications

Good knowledge of the morphological and functional anatomy of the TP has important surgical implications. This particular segment of the trigeminal system and its containing arachnoido-dural lodge, as well as the adjacent surrounding structures, constitute an anatomo-surgical entity. The TC is independent from the parasellar lodge. The latter is an interperiosteal-dural space, classically but wrongly named cavernous sinus [7], and which is in continuity with the orbit through the superior orbital fissure.

The TP is the target for most of the percutaneous lesioning procedures for treating trigeminal neuralgia, especially for the RF method [39]. At this level the somatotopic organization permits targeting to obtain a selective analgesia/hypoesthesia corresponding to the trigger zone(s) and covering the trigeminal division(s) involved, whilst sparing the rootlets not related to the clinical manifestations. RF under neurophysiological guidance, together with fluoroscopic or CT-scan control, is crucial to achieve selective lesioning of the sensory fibers with the RF procedure [17, 35, 37, 38]. Although rather infrequently performed nowadays, the open (extradural) subtemporal retrogasserian rhizotomy, as pioneered by Frazier [8], can be topographically selective if using the microsurgical and/or the endoscopic techniques. It might be also suggested that—thanks to the clear-cut somatotopy of the sensory fibers at the TP level—stereotactic radiosurgery (SRS) could predominantly focus onto targeting the (sole) rootlets that correspond to the trigger zone. Indeed, the classical target for SRS is at the TREZ; but this be at more peripheral level [43].

Mastering fine surgical anatomy of the trigeminal cave region and the contained TP can be most useful for accurate and safe microsurgical dissections and conservative tumor removals. This holds especially true for exeresis of the (small)

Table 7 Histology method of the trigeminal nerve

Histological method of study	Schiff stained	Christensen method	Frozen histological section	NA	Number of sides studied
Meckel 1748 [24]	0	0	0	0	1
Prochaska 1779 [29]	0	0	0	0	1
Krause 1896 [19]	0	0	0	0	1
Frazier 1925 [7]	0	0	0	0	1
Van Nouhys 1929 [42]	0	0	0	0	28
Kirschner 1933 [18]	0	0	0	0	1
Henderson 1965 [10]	80	80	80	650	730
Jannetta 1967 [13]	0	0	0	0	56
Gudmundsson and Rhoton 1971 [9]	0	0	0	0	50
Sweet 1974 [36]	0	0	0	0	353
Sindou, Keravel 1979 [33]	0	0	0	200	200
Kawamura 1988 [16]	0	0	0	6	6
Karol 1991 [15]	0	0	0	0	9
Sindou 1994 [32]	0	0	0	0	350
Sindou 1999 [35]	0	0	0	0	1260
Uryvaev 2008 [41]	78	78	0	0	78
Tatli 2008 [37]	0	0	0	0	100
Leston 2009 [21]	NA	NA	NA	NA	1
Alvernia 2009 [1]	0	0	0	0	4
Sindou 2010 [31]	NA	NA	NA	NA	NA
Peris-Celda 2013 [27]	0	0	0	0	36
Joo, 2014 [14]	0	0	0	0	10
Terrier 2018 [38]	0	0	0	0	22
Total	158 (6.5%)	158 (6.5%)	80 (3.2%)	856	3298

trigeminal schwannomas that arise from the TP, to save the non-attained rootlets; and in doing so, to decrease post-operative deficits as well as occurrence of corneal trophic disorders. Good knowledge may also help to deal with other types of benign tumors, among which: (soft) meningiomas enclosed in the trigeminal cave, dysembryoplastic tumors, etc. Training in the anatomical laboratory is crucial to familiarize with this fine anatomy and develop skills until satisfactory level of the learning curve be obtained.

Limitations of the study

This review of the TP anatomy has several limitations. The main one is that most authors described the TP, TG and TC without clear-cut respective distinctions, including in the surgical and electrophysiological literature. Further studying the plexual anastomoses revealed itself difficult. In addition to further anatomical and histological studies, high-Field MRI studies, cranial nerve tractography might help to better understand the plexual distribution and functional significance of the TP [12].

Conclusion

From its historical description in 1779, the triangular plexus has progressively been described as a separate TGN entity between the TG and the cisternal segment of the TGN root in the cerebellopontine angle. The TP presents *gross anatomical* (triangular shape located in the TC), *micro-anatomical* (plexual distributions of anastomoses), *electrophysiological* (somatotopic paresthesias and evoked motor responses under direct rootlet stimulation) and *histological* (sensory-, motor-, and sympathetic-anastomoses) particularities dominated by its somatotopic organization.

Table 8 Electrophysiological study of the trigeminal nerve

Electrophysiological study	Sensitive evoked potential of TGN	Stimulation at 50 Hz	Stimulation at 5 Hz	TP between the posterior petrous part and the TG	EMR corresponds to sensitive territory	Number of sides studied
Meckel 1748 [24]	0	0	0	0	0	1
Prochaska 1779 [29]	0	0	0	0	0	1
Krause 1896 [19]	0	0	0	0	0	1
Frazier 1925 [7]	0	0	0	0	0	1
Van Nouhys 1929 [42]	0	0	0	0	0	28
Kirschner 1933 [18]	1	0	0	0	0	1
Henderson 1965 [10]	0	0	0	0	0	730
Jannetta 1967 [13]	0	0	0	0	0	56
Gudmundsson and Rhoton 1971 [9]	0	0	0	0	0	50
Sweet 1974 [36]	353	0	353	0	0	353
Sindou, Keravel 1979 [33]	200	0	NA	NA	200	200
Kawamura 1988 [16]	6	0	0	6	6	6
Karol 1991 [15]	9	9	9	9	9	9
Sindou 1994 [32]	0	0	0	0	0	350
Sindou 1999 [35]	1260	0	1260	1260	1260	1260
Uryvaev 2008 [41]	0	0	0	0	0	78
Tatli 2008 [37]	0	0	0	0	0	100
Leston 2009 [21]	NA	NA	NA	NA	NA	1
Alvernia 2009 [1]	0	0	0	0	0	4
Sindou 2010 [31]	NA	NA	NA	NA	NA	NA
Peris-Celda 2013 [27]	0	0	0	0	0	36
Joo, 2014 [14]	0	0	0	0	0	10
Terrier 2018 [38]	0	0	0	0	0	22
Total	1813 (54.9%)	9 (0.3%)	1613 (52.1%)	1275 (41.1%)	1475 (47.6%)	3298

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Conflict of interest The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

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