Cell Tissue Res (1988) 251:621–631

Cell and Tissue Research

Ultrastructure of the meninges at the site of penetration of veins through the dura mater, with particular reference to Pacchionian granulations*

Investigations in the rat and two species of New-World monkeys (*Cebus apella, Callitrix jacchus*)

Brigitte Krisch

Anatomisches Institut der Universität Kiel, Kiel, Bundesrepublik Deutschland

Summary. At the sites where a vein penetrates through the dura mater, two aspects deserve particular attention: (i) The delineation of the perivascular cleft, a space belonging to the interstitial cerebrospinal fluid (CSF) compartment, toward the interior hemal milieu of the dura mater. (ii) The relationship between the perivascular arachnoid layer and the subdural neurothelium at the point of vascular penetration. These problems were investigated in the rat and in two species of New-World monkeys (*Cebus apella, Callitrix jacchus*). Concerning the first aspect, tight appositions of meningeal cells to the vessel wall, the basal lamina of which is widened and enriched with microfibrils, prevent communication between the interstitial CSF in the perivascular cleft and the hemal milieu in the dura mater. With reference to the second aspect, the perivascular arachnoid cells are transformed into neurothelial cells at the point where they become exposed to the hemal milieu of the dura mater and subsequently continuous with the subdural neurothelium. Leptomeningeal protrusions encompassing outer CSF space can penetrate into the dura mater. These protrusions may expand and branch repeatedly, forming along the wall of the dural sinus Pacchionian granulations. At these sites, however, the structural integrity of the sinus wall and the Pacchionian granulation is not lost. Numerous vesiculations not only in the sinus and vascular walls, but also in the cellular arrays of the Pacchionian granulations or paravascular leptomeningeal protrusions indicate mechanisms of transcellular fluid transport. Moreover, the texture of the leptomeningeal protrusions favors an additional function of these structures as a "volume" buffer.

Key words: Perivascular space – Cerebrospinal fluid compartments – Dura mater – Pacchionian granulations – Rat – *Cebus apella, Callitrix jacchus* (Primates)

Arterial and venous blood vessels penetrating the brain surface are surrounded by a closed, funnel-shaped pial space. They establish the following two pathways for the escape of the interstitial cerebrospinal fluid (CSF): (i) between the basal lamina covering the perivascular glial processes and the brain-exposed wall of the pial funnel, with an open communication to the subpial cleft, and (ii) between the vascular basal lamina and the vessel-exposed wall of the pial funnel, providing access to the leptomeningeal intercellular clefts and the perivascular cleft proper. The blood vessels are covered by an uninterrupted leptomeningeal layer when they traverse the outer CSF-space (Krisch et al. 1984).

Along the surface of the brain, the character of the texture of the perivascular leptomeninx at the site where the veins pass through the dura mater on their way to larger veins or to venous sinus, still awaits clarification. This aspect is important since a paravascular route open to interstitial CSF would provide a pathway between hemal intrinsic milieu of the dura and the interstitial CSF compartment. This would be an unusual construction since in all other locations studied to date a structural and/or functional barrier between the two milieus has been described (Krisch and Leonhardt 1978; Krisch et al. 1978, 1983, 1984; Krisch and Buchheim 1984; Krisch 1986). Hence, the present study is focussed on the perivascular leptomeningeal architecture of veins which penetrate the dura mater. With respect to a possible pathway of communication between the outer CSF compartment and the hemal milieu within the dura mater the fine structure of the Pacchionian granulations was re-examined.

Andres (1967a) has published a detailed description of the leptomeningeal pattern at the sites where spinal nerves penetrate the dura mater. In one of his diagrammatic figures he places emphasis on the continuity of the outer leptomeningeal layers with the perineural sheath, and even with the perivascular array of leptomeningeal cells along the borderline to the dura mater. However, focussing his attention on the mode of penetration of spinal nerves, Andres made only a general comment on the reticular character of the outer leptomeningeal layers without discussing further details. To our knowledge no exact information exists concerning the perivascular leptomeningeal texture of blood vessels that penetrate the dura mater.

* Dedicated to Professor T.H. Schiebler on the occasion of his 65th birthday

Acknowledgements. The skilled technical assistance of Mrs. Bettina Facompré is gratefully acknowledged. Supported by the Deutsche Forschungsgemeinschaft (Grant Nr. Kr 569/5-2) and the Stiftung Volkswagenwerk

Send offprint requests to: Prof. Dr. Brigitte Krisch, Anatomisches Institut der Universität Kiel, Neue Universität, Olshausenstrasse 40, D-2300 Kiel, Federal Republic of Germany

In contrast to the aforementioned situation, numerous studies have been focussed on the ultrastructure of Pacchionian granulations, albeit with contradictory results. On the one hand, they were described as protrusions of the leptomeninx containing all leptomeningeal layers (Thomas 1966; Andres 1967b; Thompson 1984), on the other hand, canaliculi were mentioned permitting direct communication between CSF and sinus blood with involvement of valve-like mechanisms (Jayatilaka 1965b; Tripathi 1974; Levine et al. 1982; Gomez et al. 1983).

Materials and methods

Six albino rats of both sexes, between 3 and 12 months of age, were used. No age-dependent or sex-related factors were noted. The animals were perfused intracardially with 25 ml Macrodex® containing 1% Procain® and 0.1% Thrombophob® via a dripping set. Subsequently, the brains were fixed by perfusion with 5% glutardialdehyde in 0.1 M cacodylate buffer, pH 7.4, using the same perfusion apparatus. The parietal bones of the skull were then cautiously removed without lesioning the dura mater. The temporal portion of the brains up to 3 mm from the midsagittal plane was removed, the parietal portion transected horizontally, and the dura mater fixed to the remaining cerebral and cerebellar tissues by use of thin catgut (Synthofil®, Braun Melsungen, FRG). Between two of these threads the long, thin tissue slices were subdivided by frontal transectioning and the tissue specimens postfixed overnight in the same fixative, rinsed in 0.1 M phosphate buffer, pH 7.4, osmicated, dehydrated and finally embedded in Araldite®.

Monkeys (*Cebus apella:* 2; *Callitrix jacchus:* 3)[1] of both sexes, body weight ranging between 1600 and 3400 g, were anesthetized with Nembutal® (50 mg/kg b.w.) injected intraperitoneally, then perfused intracardially with 0.5 ml Liquemin®, 100 ml Haemaccel® and 500 ml 2% glutardialdehyde in 0.1 M cacodylate buffer, pH 7.4 (pressure 60 mmHg). The parietal lobes of the brain covered by the bone were dissected out by a horizontal cut, and postfixed overnight. The further steps of preparation, trimming and embedding corresponded closely to those described for the rat.

Semithin sections of the frontally cut sagittal sinus and the underlying portion of the brain were scanned for vessels invading the dura mater, for islets of meningeal tissue and for Pacchionian granulations. In the rat we did not succeed in preserving the delicate veins penetrating the dura but Pacchionian granulations were found, although in lower numbers than in monkeys. Ultrathin sections were double-contrasted with uranyl acetate and lead citrate and examined with a Philips 300 electron microscope equipped with a goniometer stage.

Results

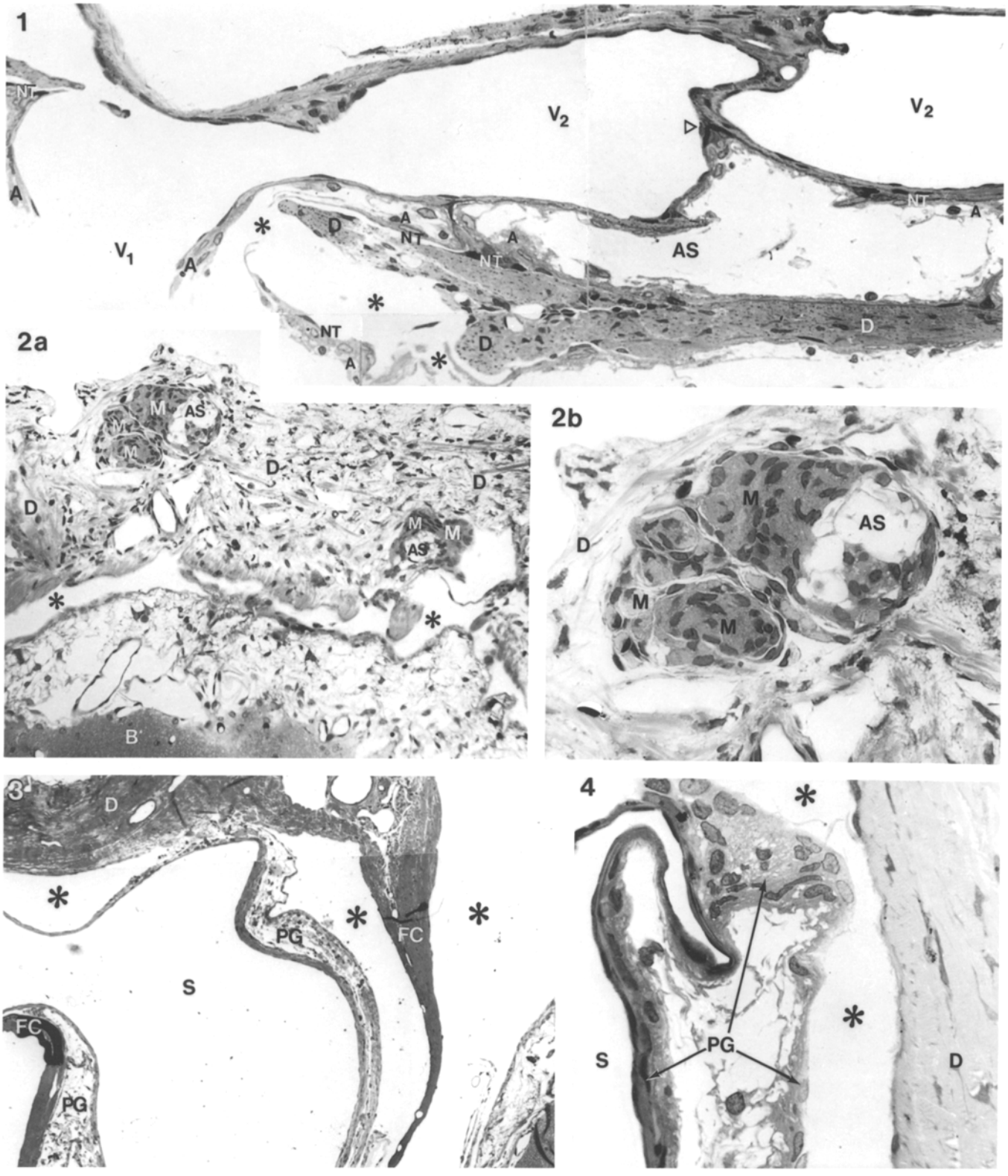
Light microscopy. At the convex surface of the brain, the veins extending from the arachnoid space to a dural vein or sinus, were always thin-walled and had wide lumina. They were devoid of a muscular layer but possessed an uninterrupted sheath of pericytes completely covered by arachnoid cells. Next to the neurothelium, in particular where the dura mater opens to allow the passage of the vein, collagen fibers appeared to be more densely arranged than in dural layers adjacent to the skull and encompassing the dural vessels. At the site where the vein penetrates the dura mater, the leptomeningeal sheath retains its continuity (Fig. 1). Leptomeningeal protrusions, continuous not only with the perivascular leptomeninx, but also with the subdural leptomeningeal layers (arachnoid, neurothelium), greatly differ in size and may intrude paravenously into the dura mater.

Such leptomeningeal protrusions are mostly compact when they belong to the short or finger-like types. Larger, club-shaped protrusions mostly contain a cell-free space, often incompletely subdivided by leptomeningeal septations (Figs. 1, 2). In the rat, such protrusions are small, do not include a true space, but contain a core of arachnoid cells continuous with the outer arachnoid layer. In *Cebus apella* and *Callitrix jacchus,* larger protrusions always possess a central, cell-free space. Via the stalk of the protrusion this space communicates with the outer arachnoid space of the brain. Such protrusions can invade the dura mater far beyond the site of entrance of the vessel; thus, deep in the pachymeninx compact or hollow islets of meningeal tissue are observed (Fig. 2). Generally but not exclusively, these tissue formations are located in the direct neighborhood of other dural blood vessels, from which they remain separated by a thin layer of connective tissue. The leptomeningeal protrusions increase in size when they reach the venous sinus in the form of Pacchionian granulations; they are closely apposed to the wall of the sinus over long distances (Figs. 3, 4). According to light-microscopic criteria there appear to be only gradual differences in size and differentation between the regular paravascular leptomeningeal protrusions at the site of penetration of a vein through the dura mater and the more elaborate Pacchionian granulations.

Electron microscopy. A cerebral vein approaches the dura mater completely covered by a few uninterrupted layers of arachnoid cells. These cells are uniform in their appearance, and as can be judged from their morphology, do not differ from arachnoid cells elsewhere in the leptomeninx. However, at the point where they traverse the gap in the dura mater, the arachnoid cells adjacent to the vascular wall transform into two forms of neurothelial cells (transformation zone): (i) electron-dense, and (ii) light elements. A single layer of electron-dense, slender cells, which are supposed to belong to the neurothelial layer (see Discussion), is attached directly to the venous wall. These electron-dense cells are covered by a second neurothelial layer consisting of light epitheloid cells. These cells are separated from the neighboring characteristic arachnoid elements by a very narrow intercellular cleft containing amorphous material and occasionally spindle-shaped accumulations of intercellular substance (Figs. 6, 7).

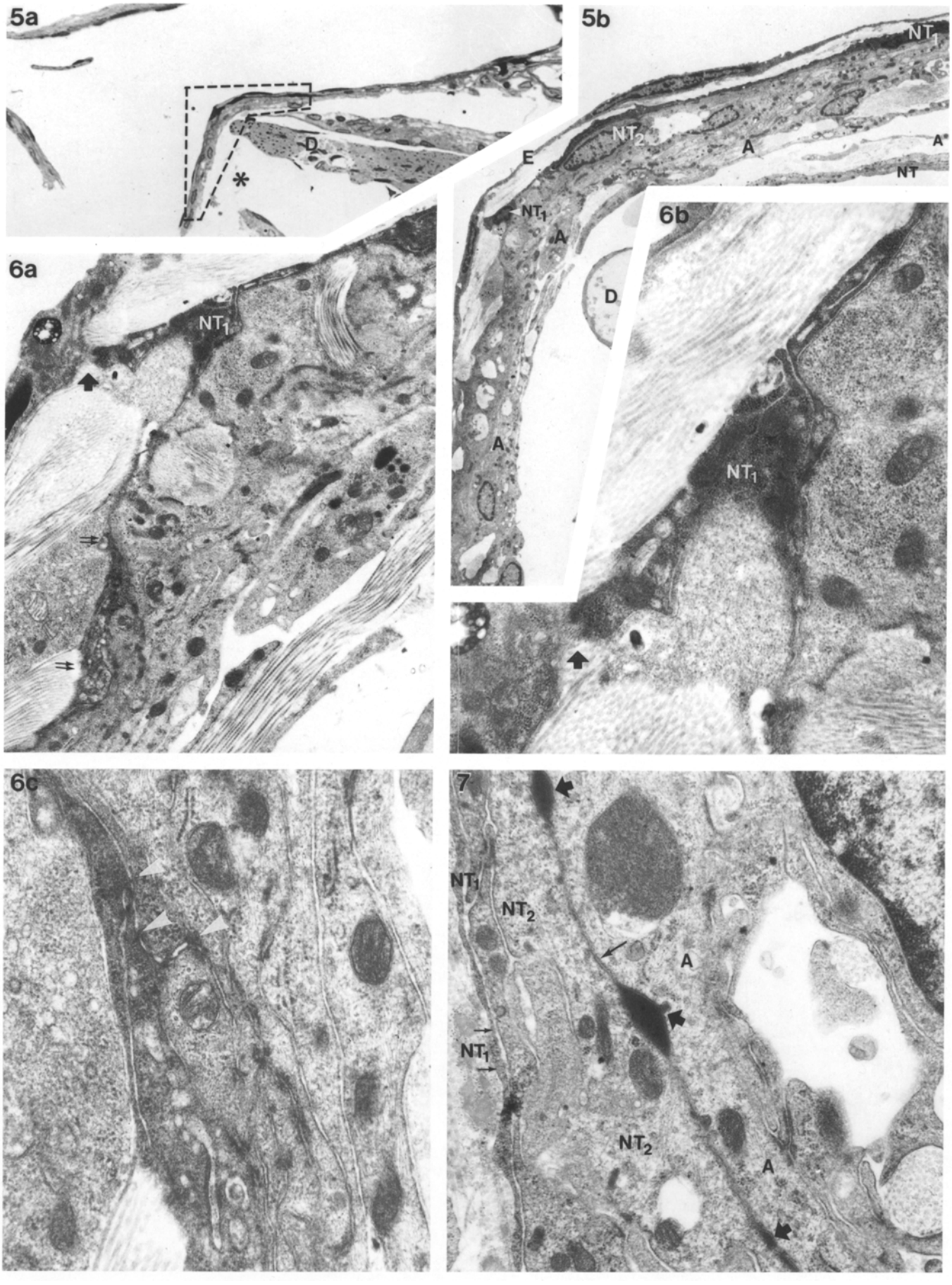
Close to the site of transformation of perivascular arachnoid cells into neurothelial cells, processes of the perivascular arachnoid cells become detached from the leptomeninx, traverse the narrow perivascular space and become closely apposed to the basal lamina of endothelial or pericytic elements (Fig. 8). This texture of closely apposed processes extends into the beginning of the transformation zone and encompasses also the electron-dense neurothelial cells.

[1] The author is greatly indebted to Professor W. Meinel and Dr. H. Erhard (Gesamthochschule Kassel) for providing the monkey brains



Figs. 1–19. In all micrographs, disruptions or artificial spaces are indicated by *asterisks*

Figs. 1–4. General view: vein entering the dura, paravascular and intradural leptomeningeal protrusions, and Pacchionian granulations; semithin sections. **Fig. 1.** *Callitrix jacchus*, vein (V_1) covered by arachnoid cells (*A*) penetrates dura mater (*D*) and joins a dural vessel (V_2). Note septated meningeal protrusion (*A, NT*); its central space is continuous with the arachnoid space (*AS*). *Triangle* detail shown in Fig. 9 at higher magnification. ×350. **Fig. 2. a** *Callitrix jacchus*, islets of meningeal tissue (*M*) partly enclose a space (*AS*) in dura (*D*) covering cerebellum (*B*). **b** Higher magnification of the left group of meningeal islets shown in **a**. a ×140, b ×560. **Fig. 3.** *Cebus apella*, collapsed venous sinus (*S*) between the two portions of the falx cerebri (*FC*). Distinct areas of the sinus wall are accompanied by meningeal tissue, including Pacchionian granulations (*PG*). ×87.5. **Fig. 4.** *Callitrix jacchus*, Pacchionian granulation (*PG*) interposed between venous sinus (*S*) and dura mater (*D*). ×560


5a
D
*
5b
NT1
NT2
A
E
NT
NT1
A
D
A
6a
NT1
6b
NT1
6c
7
NT1
NT2
A
NT1
NT2
A

In the transformation zone the cells of the venous wall, the leptomeningeal elements, as well as the electron-dense and light neurothelial arachnoid cells may display numerous pinocytotic vesicles. No intercellular contacts are observed between the vascular and the arachnoid or neurothelial cells, but the vascular basal lamina appears thickened and is associated with microfibrils, which are also found in the peripheral cytoplasm of the electron-dense neurothelial processes. Thus, in the closely apposing segments the perivascular cleft appears to be filled with thickened basal lamina material and its associated microfibrils. Occasionally, pericytes and neurothelial processes are entwined. Beyond the transformation zone signs of such close apposition are not observed.

Within the dura mater the ultrastructure of the leptomeningeal protrusions varies only with respect to their size and/or the plane of section (axial, paraxial or tangential). The ultrastructure of the Pacchionian granulations does not differ in its composition from that of the paravenous leptomeningeal protrusions. Striking architectural differences mark the distance from the outer circumference surrounded by the dura mater to the core of the protrusion. The outer layers of the granulations are formed by slender, flat, electron-dense neurothelial cells, which cover the clear neurothelial elements in the form of a very thin, single-cell layer or as a more prominent, multicellular formation (Figs. 9–11). Also transitional forms between these two extreme modes of differentation may exist. In the case of Pacchionian granulations the electron-dense neurothelial cells are arranged over considerable distances in parallel to the wall of the sinus; they are separated from the latter by a layer of collagen fibers (Fig. 12). Direct appositions of neurothelial cells to the sinus wall are rarely observed. These epithelial-like elements closely correspond in their morphology to other neurothelial cells elsewhere in the leptomeninx (Fig. 13). Among the conspicuous features of these cells are extensive Golgi areas from which granules with slightly electron-dense cores emerge. The neurothelial cells are closely entwined and connected by desmosomes, gap junctions and tight junctions (Fig. 14). Between the electron-dense and light forms of neurothelial cells, transitional forms exist, which possess a copious amount of clear cytoplasm containing numerous cytoplasmic organelles. Under certain circumstances it may be difficult to differentiate between the clear neurothelial and adjacent arachnoid cells. However, these two forms of meningeal cells are always separated by a very narrow intercellular cleft (Fig. 15), which contains fine, flocculent material or, occasionally, electron-dense precipitates filling the spindle-shaped dilatations of the intercellular space (Fig. 16).

Although the appearance and arrangement of the arachnoid cells in intradural leptomeningeal protrusions and typical Pacchionian granulations correspond closely to their features in the leptomeninx proper (e.g., intercellular contacts, intercellular spaces containing collagen, short fragments of basal lamina and associated hemidesmosomes), they are more conspicuous than the other leptomeningeal elements because of their numerous pinocytotic vesicles. These vesicles indicate a kind of cellular activity that, in all leptomeningeal cell layers of the protrusions, appears to be increased in comparison to the leptomeninges elsewhere in the brain. This pinocytotic activity differs among the leptomeningeal protrusions and Pacchionian granulations in one and the same animal. Conspicuous species differences could not be observed. The same holds true also for the components of the vascular wall (Figs. 17–19).

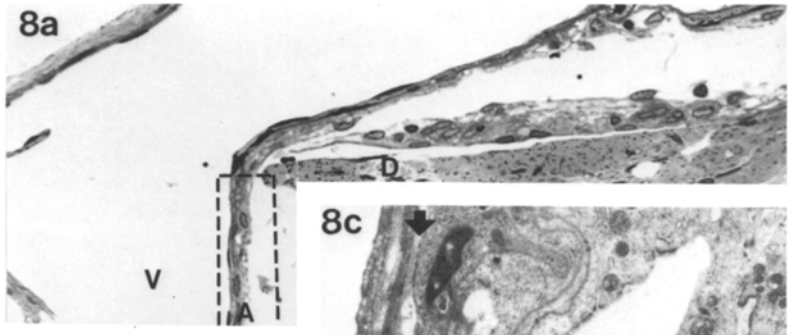
Discussion

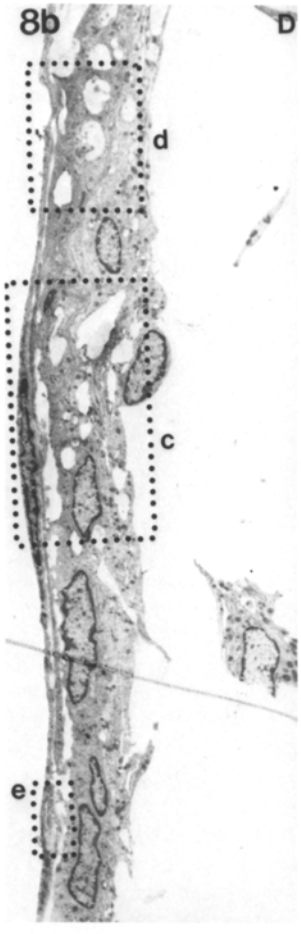
The present results show the continuity and integrity of all leptomeningeal layers at the point where veins penetrate into the dura mater. These leptomeningeal cells form paravascular protrusions, the interior space of which is in continuity with the arachnoid space. Such protrusions invade the dura mater as finger- or club-like bodies, endowed with indentations and incomplete septa. When increasing in size, they become apposed to the wall of the venous sinus in the form of Pacchionian granulations. In such protrusions of different types all leptomeningeal layers, which generally establish the border layer to the dura mater, do persist. The endothelium of the venous sinus is intact. No communication between the interstitial compartments in the vascular wall and the leptomeningeal space could be observed. At the site of vascular entrance into the dura mater leptomeningeal processes are closely attached to the vascular wall and transform into neurothelial elements as soon as they become exposed to the hemal milieu of the dura mater. For a schematic representation of these observations, see Fig. 20.

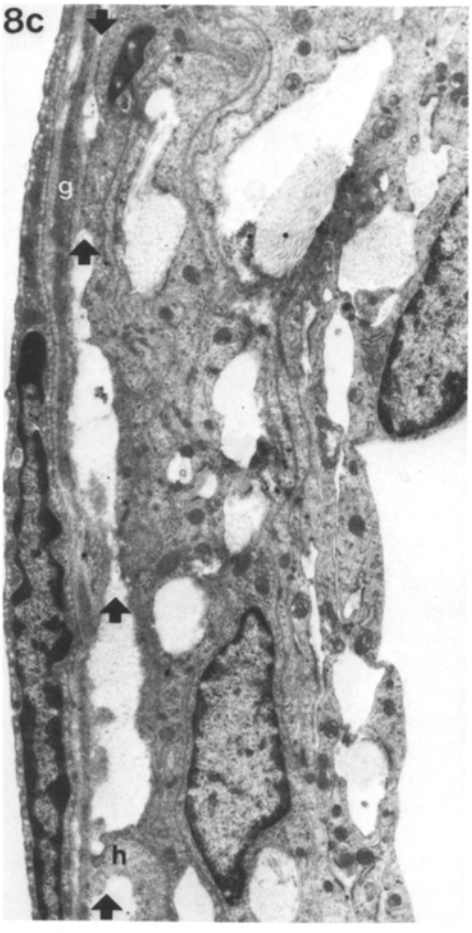
In previous reports (Krisch et al. 1983, 1984), the term "inner dura layer" was used to describe the flat, electron-dense elements separating the light, epithelial-like neurothelial cells from the dura mater proper. More recent results on the ultrastructure and barrier function of the tela choroidea (Krisch 1986) indicate that leptomeningeal cells in general (i.e., also cells of the pial layer) may transform into both types of neurothelial elements when facing a hemal milieu. This finding is substantiated by the present results, which indicate a spatial continuity between the arachnoid proper and both types of neurothelial cells within the leptomeningeal formation.

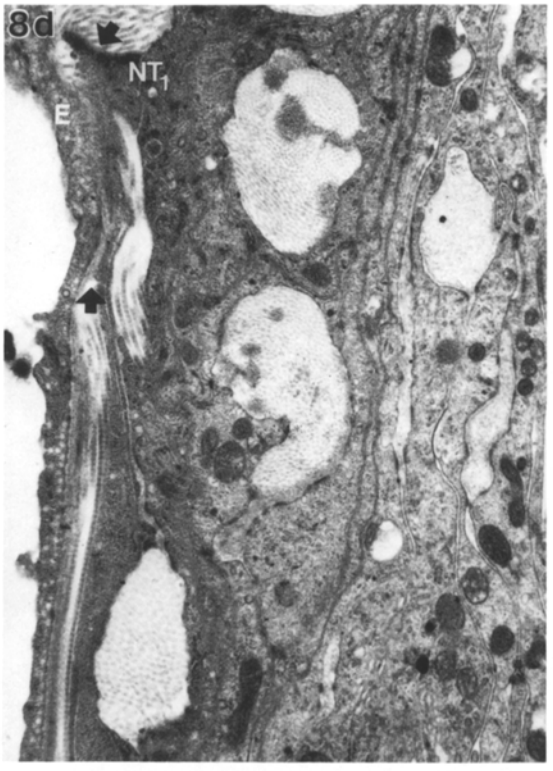
The primary aim of the present study was to elucidate the problem of a possible open communication between the humoral milieu dominating in the perivascular space (component of the interstitial CSF compartment) and the hemal milieu in the dura mater along the intrameningeal course of a vein. In this connection the only structures that may be involved in the control of the perivascular space are the regularly occurring close appositions of the innermost perivascular leptomeningeal and neurothelial cells to

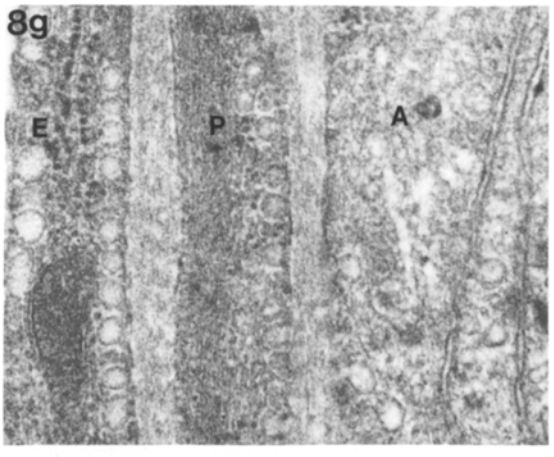
Figs. 5–7. *Callitrix jacchus*, perivascular leptomeninx of a vein penetrating the dura (*D*). **Fig. 5. a** Light-microscopic semithin section; *framed area* shown in **b**. **b** Perivascular arachnoid layer (*A*) at the brain-apposed aspect of the vessel (*E* endothelium) is connected with slender, electron-dense (NT_1) and light, epithelial-like (NT_2) neurothelial cells; *A* arachnoid, *D* dura. a ×350, b ×2400. **Fig. 6a–c.** ~600 nm distant from the section shown in 5b; an electron-dense neurothelial cell (NT_1) contacts endothelial cell (*arrowhead;* shown at higher mangification in **b**) and is entwined with arachnoid cells (*double arrows*, shown at higher magnification in **c**); between both cell types numerous intercellular contacts (*white arrowheads* in **c**). a ×11000, b ×22700, c ×36630, tilting angle −43°. **Fig. 7.** Paravascular slender, electron-dense (NT_1) and light, epithelial-like (NT_2) neurothelial cells separated from arachnoid cells (*A*) by a narrow intercellular cleft (*arrow*) containing electron-dense intercellular substance (*arrowhead*). ×22700

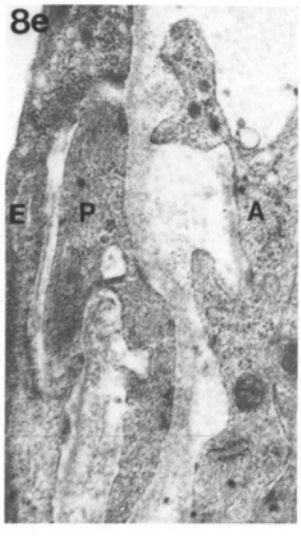

8a
D
V
A


8b
D
d
c
e

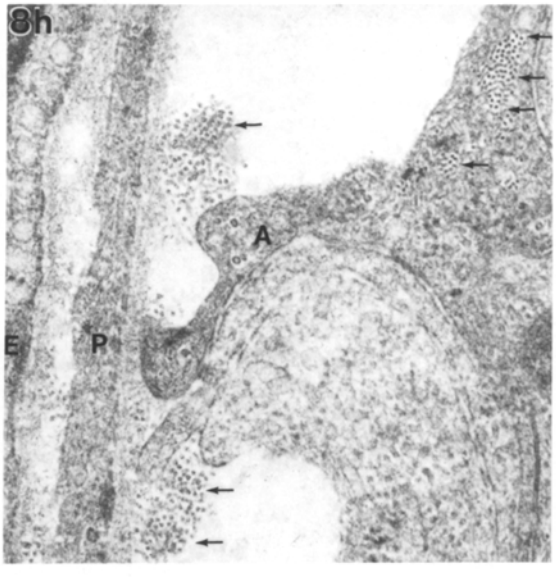

8c
g
h


8d
NT1
E


8g
E
P
A


8e
E
P
A


8f
E
P
A


8h
E
P
A

the perivascular basal lamina. In these areas the perivascular space is reduced to the width of the basal lamina and its associated microfibrils, which are obviously produced by neurothelial cells.

Preliminary light-microscopic investigations using the alcian blue (pH 1) – PAS staining procedure did not contribute to the identification of the ground substances that might be associated with the perivascular cleft at the site of the vascular penetration through the dura mater. The identification of this charge of ground substance was not successful because in the vicinity of the venous sinus the dura mater displays an overall strongly positive reaction to alcian blue (pH 1), which does not allow to distinguish special features at the point of vascular penetration through the dura mater. Moreover, the light-microscopic resolution of brain structures from specimens fixed with Bouin's fluid is not sufficient to provide detailed information. Hence, it can only be hypothesized that the close apposition of leptomeningeal and neurothelial cells to the vascular wall, paralleled by a narrowing of the perivascular space, leads to a retardation of transport processes along this cleft, exposing the different molecules to the molecular sieve of the basal lamina and its associated ground substance.

In addition, it has to be considered that the interstitial CSF passing from the neuropil along small and larger veins via the arachnoid space is exposed to metabolically active meningeal cells (Wright et al. 1971; Friedman and Davis 1980; Ebersolt et al. 1981; Kaplan et al. 1981; Palmer and Palmer 1983; Sievers et al. 1983), which may be of influence on the composition of the CSF. Furthermore, after labeling the interstitial compartment of the brain with horseradish peroxidase, the reaction product appeared in the leptomeningeal intercellular clefts up to the neurothelial layer; however, a diffuse staining of the dura mater was never observed (Krisch et al. 1983, 1984). This latter staining effect could only then be expected if the perivascular space of a cerebral vein were to open freely into the perivascular spaces of dural veins located in the dura mater proper. Thus, a functional barrier can be suggested to exist between the CSF- and blood-dominated milieus at the site of penetration of cerebral veins through the dura mater. Here the situation is clearly different from that of nerves passing through the dura mater and entering peripheral tissue compartments. The neurothelium is continuous with the perineural sheath (Andres 1967a), within which the CSF is supposed to flow in a peripheral direction (Földi et al. 1960; Arnold et al. 1972; Stober 1972).

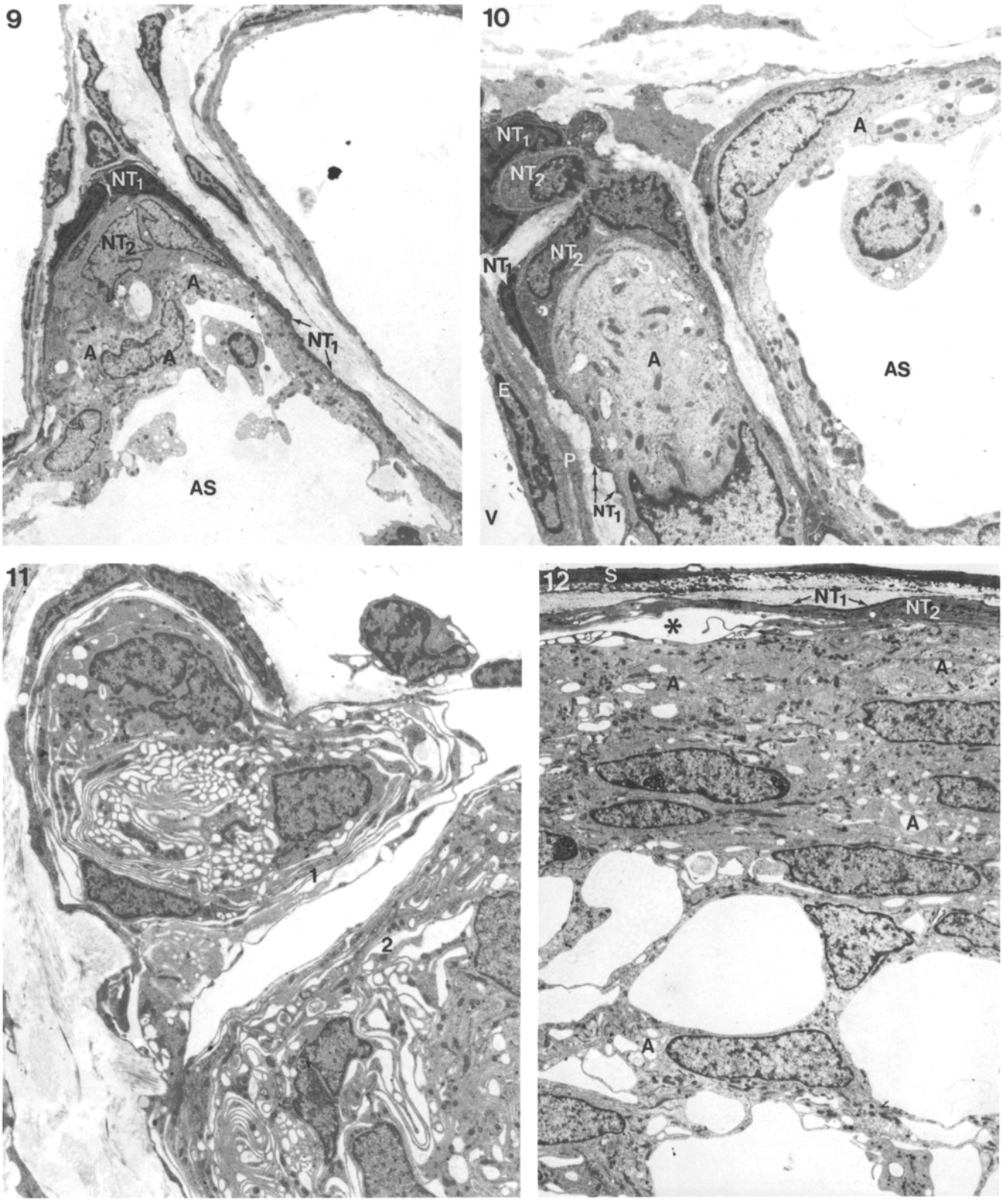
Much more striking than this functional barrier is the persistence of the arachnoid space as an entity, enclosed by all leptomeningeal layers which form its borderline toward the dura mater. Although the leptomeningeal protrusions may invade deeply into the dura mater, there is no indication of a communication between the leptomeningeal space and the vascular lumen.

These results confirm earlier findings of Cooper (1958, man), Thomas (1966, man), Andres (1967b, dog, cat) and Thompson (1984, rat, man), who described the Pacchionian granulations as protrusions of all leptomeningeal layers. Andres (1967b) and Thompson (1984) reported indentations of the vascular wall into lobular complexes of the Pacchionian granulations, a finding that could not be observed in the present material. Such images, however, may depend on the perfusion and/or fixation procedures. The existence of a central space in larger protrusions and granulations, a lumen that is continuous with the arachnoid space, probably reflects species differences, depending on the size of the granulations. In the rat (present study), dog, and cat (Andres 1967b), this kind of space was not observed; in *Cebus apella* and *Callitrix jacchus* (present study), and also in man (Cooper 1985) it belonged to the regular structural features. However, it should be kept in mind that (i) the stalk by which the protrusion is linked to the cerebral leptomeninx is very thin, and (ii) for a precise reconstruction of the irregular forms of larger lobular or complex protrusions and granulations serial sectioning is an essential prerequisite.

The present observations indicating the existence of an intact, complete leptomeninx in protrusions and Pacchionian granulations are, however, in contradiction to several reports concerning the situation in sheep (Jayatilaka 1965a, b), monkey (Tripathi 1974) and man (Levine et al. 1982; Gomez et al. 1983). These transmission- and/or scanning electron-microscopic observations were interpreted in favor of an open communication between the sinus wall and the arachnoid space. With reference to the micrographs of these authors, however, the question arises whether in the material examined the leptomeningeal and sinus-wall tissues were free of preservation artifacts. In the electron micrographs presented by these authors, the cells indicated as "sinus endothelia" lack a basal lamina; the endothelial opening into the arachnoid space obviously represents a folded process of a single cell of unknown nature, and neurothelial and/or arachnoid tissues are missing (compare Jayatilaka 1965b; Tripathi 1974; Levine et al. 1982). When strict cytological criteria are applied, for example an intact endothelial basal lamina regarded as a crucial structural parameter, superficial intercellular clefts between electron-dense neurothelial cells (partly dilated by tissue shrinkage) should not be misinterpreted as 'blood vessels'.

Concerning the function of leptomeningeal protrusions, the abundance of pinocytotic vesicles in all cellular elements forming these bodies favor a transcellular flux of fluid, a supposition that is in accordance with previous concepts (Cooper 1958; Thomas 1966; Andres 1967b). The capacity of fluid exchange appears to be increased in the protrusions and granulations compared to the leptomeningeal tissue proper, especially supported by the fact that the surface area is enlarged in the protrusions and granulations. A further functional aspect may arise regarding (i) the density of collagen tissue in the dura, and (ii) the thickness of the walls encompassing the arachnoid space in the complex and subseptated protrusions. In both latter types of protrusions

Fig. 8a–h. *Callitrix jacchus,* relationship between arachnoid cells (*A*) and the vascular wall (*V*), shortly before vein penetrates dura mater (*D*), corresponding to the *framed area* in **a. b** Low-magnification micrograph in which the details indicated in c–h are shown. *Upper right corner,* note dura (*D*) for orientation and comparison with **a. c** Four appositions (*arrowheads*) of meningeal cells to the vessel wall, two of them shown at higher mangification in **g** and **h. d** Terminal processes of electron-dense neurothelial cells (*arrowhead*) closely attached to the endothelium (*E*). **e** and **f, g, h** Apposed processes of pericytes and arachnoid cells, in **h** associated with microfibrils (*arrows*). Note increased thickness of vascular basal lamina and numerous pinocytotic vesicles; *E* endothelium; *P* pericyte; *A* arachnoid. a ×350, b ×2443, c×8285, d ×13194, e ×22704, f ×36630, g, h ×45144; tilting angle −17°



Figs. 9–12. *Callitrix jacchus*, different forms of leptomeningeal protrusions and granulations. **Fig. 9.** Paravenous protrusion (compare Fig. 1) composed of electron-dense, slender (NT_1) and light, epithelial-like (NT_2) neurothelial cells, and arachnoid cells (A). Note central space (*AS*). ×1600. **Fig. 10.** Irregularly-shaped protrusion close to a dural vessel (*V*; *E* endothelium, *P* pericyte); its wall is composed of neurothelial cells (NT_1, NT_2), arachnoid cells (*A*) and in part encloses a central space (*AS*). ×4136. **Fig. 11.** Tangential section through a large, complex leptomeningeal granulation displaying septations and consisting of two incompletely separated parts (*1, 2*). ×4136. **Fig. 12.** Portion of a Pacchionian granulation extending along the venous sinus (*S*). The wall of the granulation is composed of neurothelial cells (NT_1, NT_2) and arachnoid cells (*A*). ×2886

Fig. 13. *Callitrix jacchus*, slightly higher magnification of the Pacchionian granulation shown in Fig. 12, covered by slender, electron-dense neurothelial cells (NT_1). At *x* it cannot been determined (even at higher magnifications) whether the cell ramifies and penetrates between the collagen fibers (*C*) to become apposed to a pericyte (*P*) in the sinus wall (*E* endothelium); NT_2 epithelial-like neurothelial cells, *A* arachnoid cells. ×14260

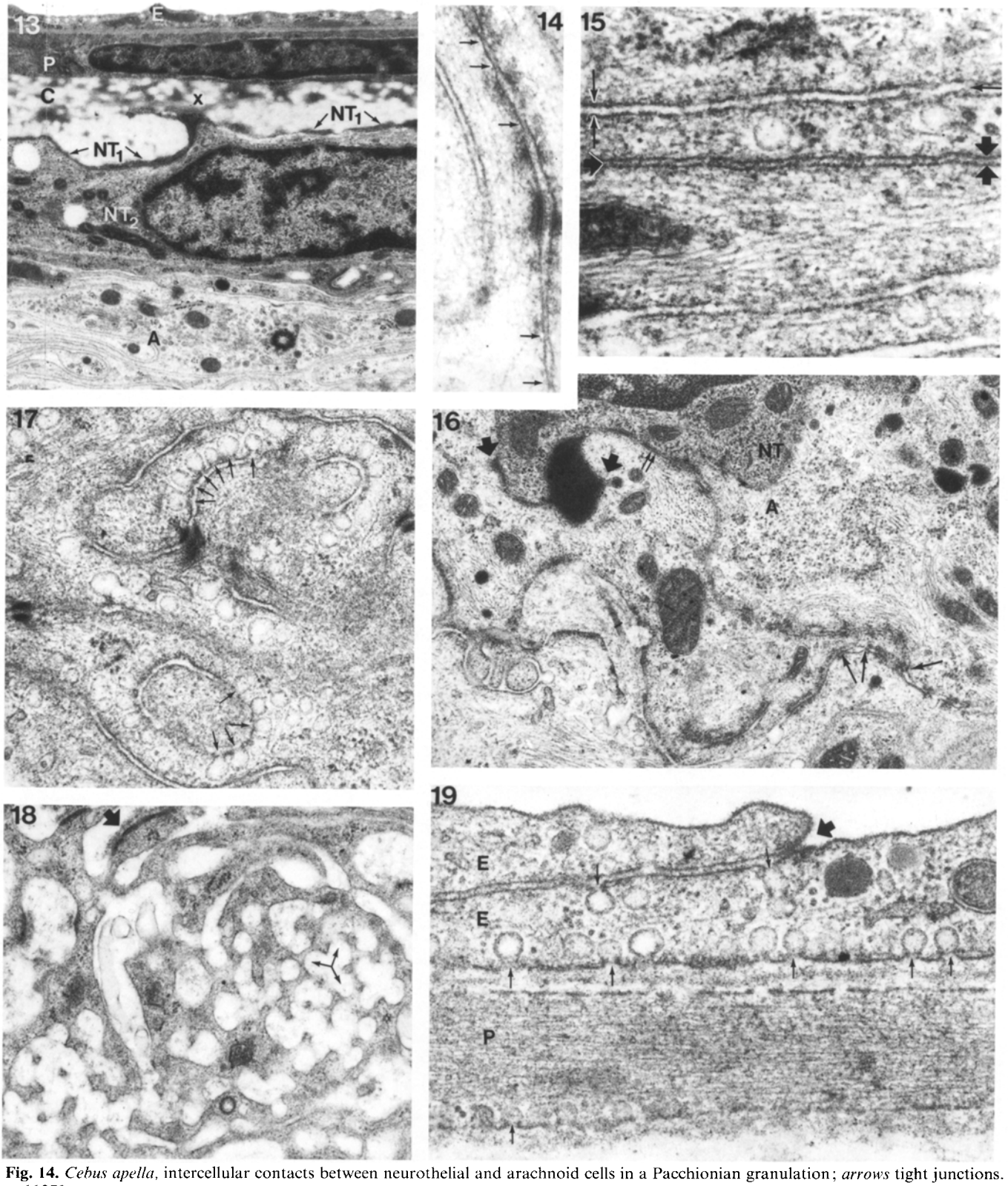


Fig. 14. *Cebus apella,* intercellular contacts between neurothelial and arachnoid cells in a Pacchionian granulation; *arrows* tight junctions. × 66270

Fig. 15. *Cebus apella,* narrow intercellular cleft (*arrowhead*) between neurothelial and arachnoid cells; compare with the upper intercellular cleft (*arrows*) displaying regular extension. × 82880; tilting angle +21°

Fig. 16. Rat, electron-dense intercellular substance (*arrowheads*) between neurothelial (*NT*) cells; intercellular contacts (*arrows*) between arachnoid (*A*) cells; note the narrow intercellular cleft (*double arrows*). × 25080

Figs. 17–19. Vesiculations and pinocytotic vesicles in all cellular components of the Pacchionian granulation and the sinus wall. **Fig. 17.** *Cebus apella,* rows of pinocytotic vesicles in arachnoid cells (*arrows*). **Fig. 18.** *Callitrix jacchus,* tangential section of arachnoid cells endowed with confluent vesiculations (*arrows*); *arrowheads* short segments of basal lamina and associated hemidesmosomes. **Fig. 19.** *Cebus apella,* pinocytotic vesicles in endothelial cells (*E*) and in a pericyte (*P*) of the sinus wall (*arrows*); *arrowhead* interendothelial tight junction. 17: × 36630; 18: × 25080; 19: × 57640

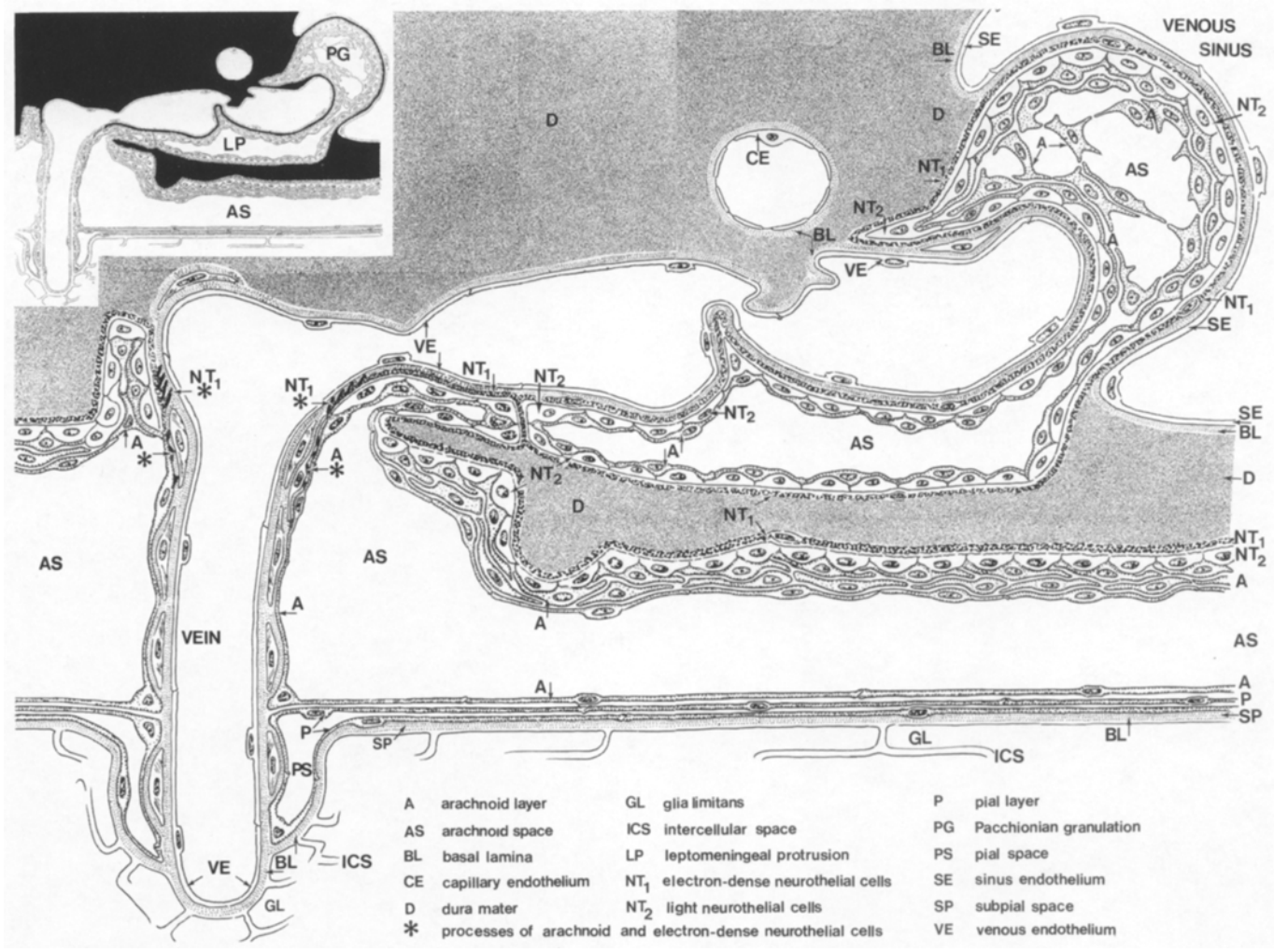


Fig. 20. Schematic drawing of a vein traversing the arachnoid space and penetrating the dura mater toward the venous sinus. *Inset* The vein is accompanied by a leptomeningeal protrusion (*LP*); a Pacchionian granulation (*PG*) bulges into the venous sinus; *black* hemal milieu of the dura mater; *clear* CSF-dominated milieu. In the overall schematic representation the cellular composition of the subseptated, paravenous leptomeningeal protrusion and the tangentially sectioned Pacchionian granulation is shown

the number of arachnoid and neurothelial cell layers appears to exceed that characteristic of large, non-subseptated protrusions. This means that in highly septated protrusions the surface area is increased; the fluid, however, has to pass an increased number of cell layers. It seems likely that the complex and septated protrusions function as a volume "buffer tank" for outer CSF, enabling rapid fluid exchange when increased fluid volume spreads out along the inner framework.

References

Andres KH (1967a) Über die Feinstruktur der Arachnoidea und Dura mater von Mammalia. Z Zellforsch 79:272–295

Andres KH (1967b) Zur Feinstruktur der Arachnoidalzotten bei Mammalia. Z Zellforsch 82:92–109

Arnold W, Nitze HR, Ritter R, v. Ilberg Ch, Ganzer U (1972) Qualitative Untersuchungen der Verbindungswege des Subarachnoidalraumes mit dem lymphatischen System des Kopfes und des Halses. Acta Otolaryngol 74:411–424

Cooper ERA (1958) Arachnoid granulations in man. Acta Anat 34:187–200

Ebersolt C, Perez M, Vassent G, Bockaert J (1981) Characteristics of the β_1- and β_2-adrenergic-sensitive adenylate cyclases in glial cell primary cultures and their comparison with β_2-adrenergic-sensitive adenylate cyclase of meningeal cells. Brain Res 213:151–161

Földi M, Gatai G, Papp N, Eöllös Z, Mezaros A (1960) Abtransport von corpusculären Teilchen aus dem Subarachnoidealraum beim Hund. Z Ges Exp Med 133:110–112

Friedman AH, Davis JN (1980) Identification and characterization of adrenergic receptors and catecholamine-stimulated adenylate cyclase in dog pial membranes. Brain Res 183:89–102

Gomez DG, Ehrmann JE, Potts DG, Pavese AM, Gilanian A (1983) The arachnoid granulations of the newborn human: An ultrastructural study. Int J Dev Neurosci, Vol 1, pp 139–147

Jayatilaka ADP (1965a) Arachnoid granulations in sheep. J Anat 99:315–327

Jayatilaka ADP (1965b) An electron microscopic study of sheep arachnoid granulations. J Anat 99:635–649

Kaplan GP, Hartmann KB, Creveling CR (1981) Localization of catechol-O-methyltransferase in the leptomeninges, choroid plexus and ciliary epithelium: Implications for the separation of central and peripheral catechols. Brain Res 204:353–360

Krisch B (1986) The functional and structural borders between the CSF- and blood-dominated milieus in the choroid plexuses and the area postrema of the rat. Cell Tissue Res 245:101–115

Krisch B, Buchheim W (1984) Access and distribution of exogenous substances in the intercellular clefts of the rat adenohypophysis. Cell Tissue Res 236:439–452

Krisch B, Leonhardt H (1978) The functional and structural border between the CSF- and blood-milieu in the circumventricular organs (organum vasculosum laminae terminalis, subfornical organ, area postrema) of the rat. Cell Tissue Res 195:485–497

Krisch B, Leonhardt H, Buchheim W (1978) The functional and structural border of the neurohemal region of the median eminence. Cell Tissue Res 192:327–339

Krisch B, Leonhardt H, Oksche A (1983) The meningeal compartments of the median eminence and the cortex. A comparative analysis in the rat. Cell Tissue Res 228:597–640

Krisch B, Leonhardt H, Oksche A (1984) Compartments and perivascular arrangement of the meninges covering the cerebral cortex of the rat. Cell Tissue Res 238:459–474

Levine JE, Povlishock JT, Becker DP (1982) The morphological correlates of primate cerebrospinal fluid absorption. Brain Res 241:31–41

Palmer GC, Palmer SJ (1983) Adenylate cyclase sensitivity to catecholamines and forskolin in rat pia-arachnoid and cerebral microvessels. Neuropharmacology 22:213–221

Sievers H, Sievers J, Baumgarten HG, König N, Schlossberger HG (1983) Distribution of tritium label in the neonate rat brain following intracisternal or subcutaneous administration of ^{3}H-6-OHDA. An autoradiographic study. Brain Res 275:23–45

Stober B (1972) Über Bewegung und Drainage des Liquor cerebrospinalis beim Kaninchen. Untersuchungen mit einer standardisierten Methode. Z Anat Entwickl Gesch 135:307–316

Thomas H (1966) Licht- und elektronenmikroskopische Untersuchungen an den weichen Hirnhäuten und den Pacchionischen Granulationen des Menschen. Z Mikrosk Anat Forsch 75:270–327

Thompson DNP (1984) Arachnoid villi and granulations in the rat and man. New considerations based on light and scanning electron microscopy. J Anat 138:568

Tripathi R (1974) Tracing the bulk outflow route of cerebrospinal fluid by transmission and scanning electron microscopy. Brain Res 80:503–506

Wright PM, Nogueira GJ, Levin E (1971) Role of the pia mater in the transfer of substances in and out of the cerebrospinal fluid. Exp Brain Res 13:294–305

Accepted August 21, 1987