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Aspects on Endolymphatic Sac Morphology and Function

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Summary. Morphological evidence indicate that the main function of the endolymphatic sac is to act as a reabsorptive and defensive mechanism for the inner ear. This activity is markedly enhanced in labyrinthine trauma, such as injection of foreign particles into the labyrinth, blocking of the endolymphatic duct, and cryosurgical destruction of vestibular sensory epithelia. Light and dark epithelial cells of the intermediate portion of the sac are capable of reabsorbing endolymph and digesting cellular debris respectively. The extensive capillary network surrounding the endolymphatic sac exhibits endothelial characteristics suggestive of active fluid transport. The "*dynamic-flow theory*" of endolymph circulation suggests that a radial-flow should be considered for energy metabolism and ion exchange around the sensory cell regions whereas a longitudinal-flow should be considered for reabsorption of endolymph and disposal of high molecular waist products and debris by the endolymphatic sac. The earlier concepts of endolymph circulation thus need not any longer be considered conflicting.

Key words: Endolymphatic Sac – Reabsorptive and Defensive Mechanism – Active Fluid Transport – Dynamic-Flow Theory.

Since the discovery of the aqueducts of the human inner ear by Cotugno (1774), and the first description of the endolymphatic sac proper by Boettcher (1869), it has been said to have many functions for the inner ear:

To be a rudimentary organ without any specific function (Siebenmann, 1919).

To produce endolymph (Boettcher, 1869; Seymor, 1954).

To resorb endolymph (Iwata, 1924; Guild, 1927; Lundquist, 1965 and others).

To act as a passive pressure regulator for the inner ear (Kolmer, 1923; Allen, 1964).

The first solid investigation based on histological analysis and experimental data was by Guild (1927). The following discussion and description is based on the first electron microscopical analysis of the endolymphatic sac by Lundquist and coworkers (1964, 1965) as well as later investigations.

Morphology

Gross Anatomy of the Endolymphatic Sac

The endolymphatic duct arises from the junction of the saccular and utricular ducts at the medial wall of the vestibule and continues running inside the vestibular aqueduct. In the posterior half of this duct, the true sac is formed as a dilatation extending through the external orifice of the vestibular aqueduct. The sac is at that part enclosed in a dural duplicature and ends in close contact with the sigmoid sinus (Fig. 1).

According to Guild (1927), the endolymphatic sac proper can be divided in three parts: *The proximal* constituting the first widening part inside the vestibular aqueduct. *The intermediate*, partly inside and partly outside the vestibular aqueduct. This latter part has also been called rugose (Bast and Anson, 1949) due to its irregular appearance with epithelial folds and crypts. *The distal part* is somewhat flattened and lies in close contact with the sigmoid sinus. It has a very narrow lumen without crypts or protrusions (Fig. 1).

Fine Structure

By electron microscopy a clear description can be given of the cellular appearance in the various parts of the endolymphatic duct and sac system.

Endolymphatic Duct: The epithelium is of a simple squamous or low cuboidal type resting on a smooth basement membrane.

The Endolymphatic Sac: *The proximal portion.* This gradually widening part of the sac has an epithelial lining which changes into a higher cuboidal cell type with small microvilliform protrusions on its endolymphatic surface (Fig. 2). *The intermediate portion.* This constitutes the main part of the sac. In the epithelial crypts and protruding papillae (Fig. 2) two distinct types of cells are recognized, the so-called *light cell* with a homogenous relatively pale matrix, richly abundant ribosomes and mitochondria, and on its fluid surface a presence of numerous microvilli and pinocytotic vacuoles (Fig. 3).

The basal part of this cell also exhibits an extensive infolding of its basal cytoplasm indicating an increased surface activity. *The dark cell* on the other hand is more wedge-shaped with a dense cytoplasm a fibrillous inappearance (Fig. 3). *The distal portion* exhibits a more cuboidal epithelial lining. Although the epithelial crypts and protruding papillae here disappears, the same basic cell types can still be recognized except in the extreme and where the cells are cuboidal in appearance.

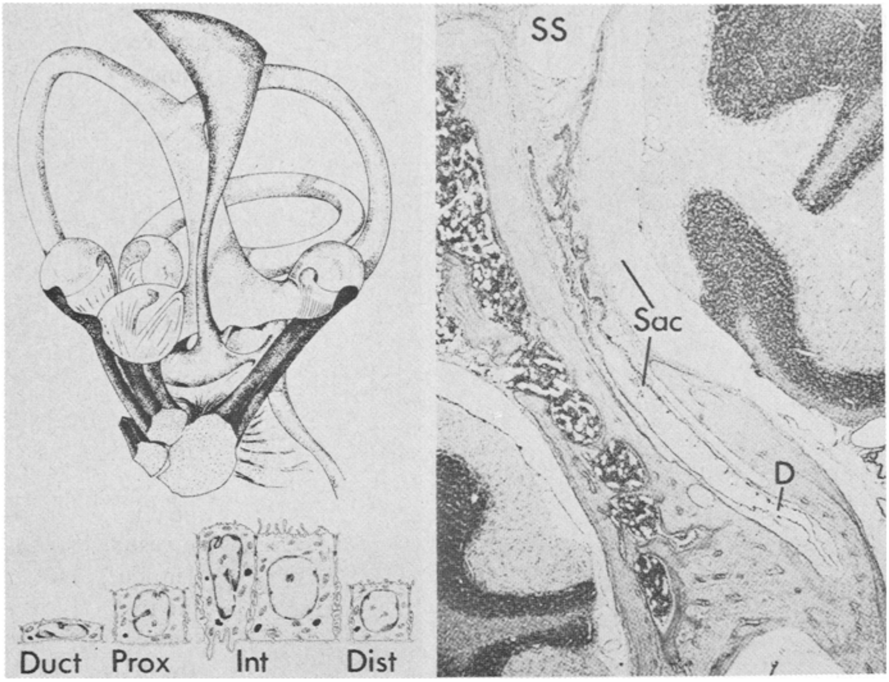

Fig. 1. Schematic drawing of labyrinth with endolymphatic sac. The various cell types are indicated in the endolymphatic duct (Duct) and in the proximal (Prox) intermediate (Int) and distal (Dist) part of the endolymphatic sac. Note that in the intermediate part two different types of cells are present. On the right picture the endolymphatic sac can be seen protruding out of the vestibular aqueduct. D = endolymphatic duct. Sac = endolymphatic sac. SS = sigmoid sinus

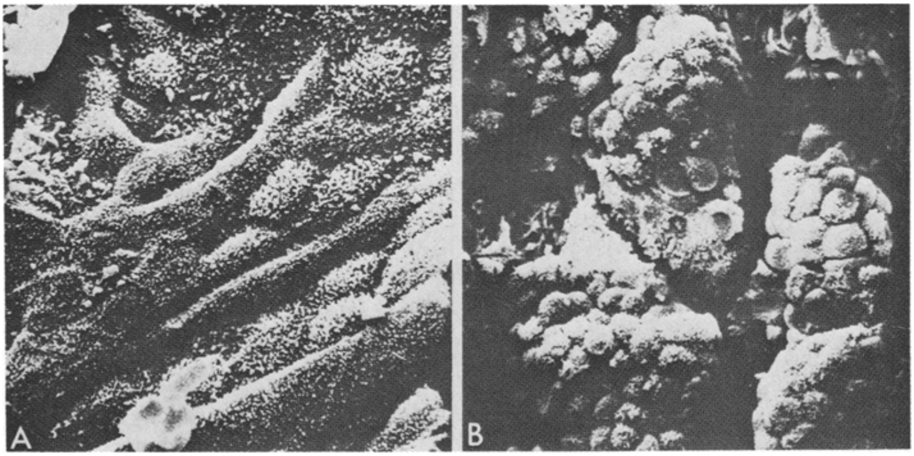

Fig. 2. A In the duct and also in the proximal part of the sac the endolymphatic surface is smooth. The cells however exhibit a few microvilli. **B** In the intermediate or rugose part of the sac true crypts are formed between protruding epithelial papillae (A, B, scanning electron microscopy)

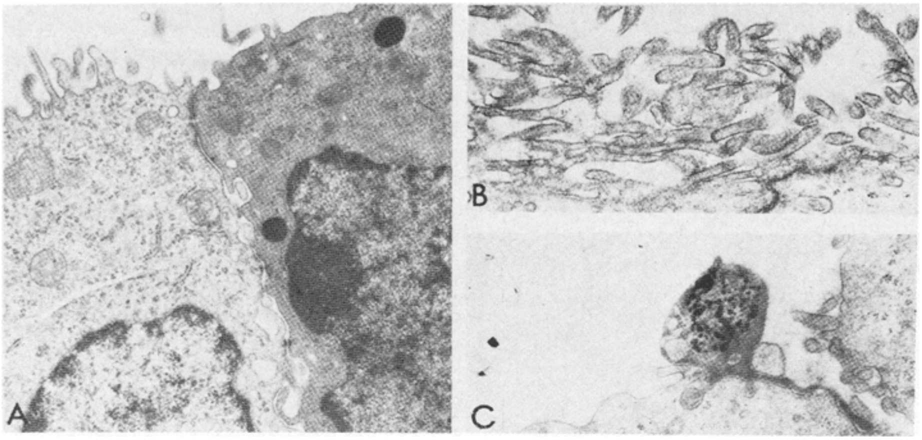

Fig. 3. A In the intermediate part of the sac a light (left) and dark (right) cell type is present. **B** The light cell often exhibits abundant microvilliform processes on its endolymphatic surface. **C** The dark cell is active in removal of debris by phagocytosis (A, B, C, transmission electron microscopy)

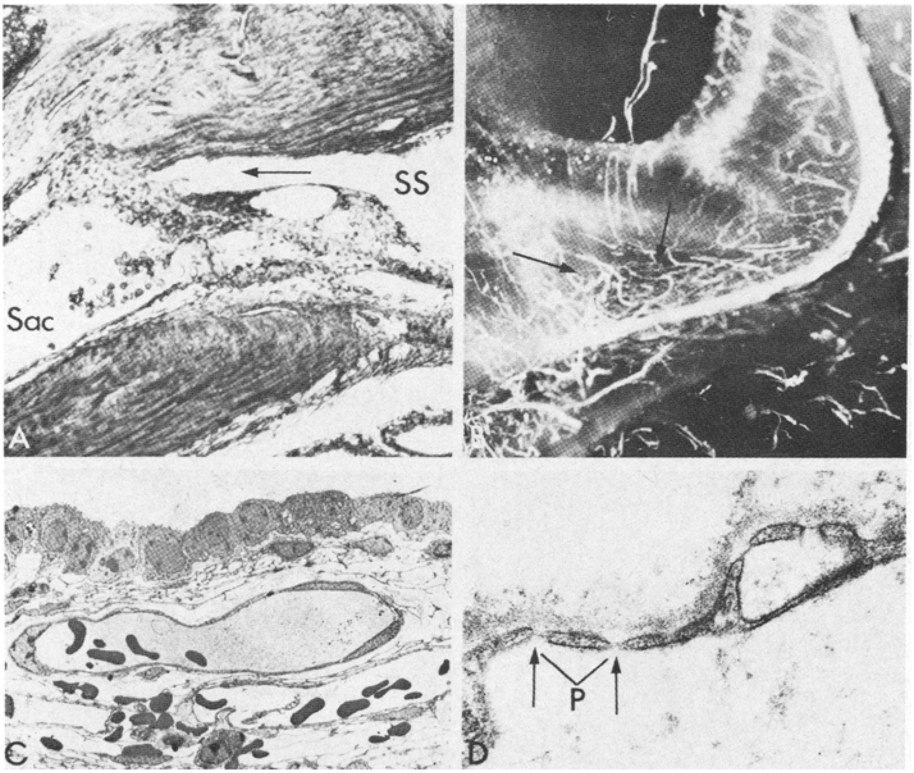

Fig. 4. A rich capillary net-work surrounds the endolymphatic sac. **A** A venule (arrow) begins deep in the connective tissue of the endolymphatic sac. Sac = endolymphatic sac. SS = sigmoid sinus. **B** With intra arterial injection a rich capillary net-work surrounding the endolymphatic sac can be demonstrated (arrow). **C** The capillaries beneath the epithelial lining of the intermediate and distal part of the sac are large and exhibit micropores indicative of an active fluid transport. **D** Detail of pores (P) in capillary endothelial wall. (A, light microscopy; B, intraarterial injection; C, electron microscopy)

Firstly described by Iwata (1924) and Guild (1927), the lumen of the endolymphatic sac is normally provided with a population of spherical so-called free floating macrophages, the origin of which are still uncertain.

Comments

The distinctive cell types present in the intermediate, or rugose part of the endolymphatic sac are indicative of an active function. The numerous microvilli together with the pinocytotic vesicles and increased cytoplasmic surface at the cell bottoms are signs of active fluid transport by the light cells. The debris often found adhering to the fluid surface of the dark cells suggest a possible phagocytotic function.

Experimental data as described below further support these suggestions.

Vascular Supply of the Endolymphatic Duct and Sac

The endolymphatic duct is partly supplied with blood from the branch of the internal auditory artery following the vestibular aqueduct. Most of the blood supply however is derived from a branch of the posterior meningeal artery which penetrates the dura and connective tissue around the endolymphatic sac forming a plexus around the widening part of it. The capillaries in the loose connective tissue are unique in the inner ear because of the presence of numerous micropores, fenestrations, in the endothelial walls. Such pores are described particularly with relation to epithelial cells active in fluid transport as first described in the kidney by Rhodin (1962) (Fig. 4).

Comments

From the extensive vascular bed surrounding the active intermediate part of the sac, the presence of pores are indicative of active fluid transport, the suggestion of the endolymphatic sac having a reabsorptive function is further strengthened. A passive dilatation of the sac functioning as a pressure relief "balloon" is not supported by the appearance of the subepithelial connective tissue. This is loose, areolar in type without any elastic fibrils or adjoining smooth muscle cells.

Experiments on Endolymphatic Sac Function

The first experimental investigation on the function of the endolymphatic sac was by Guild (1927) who injected potassium ferrocyanide into the cochlear duct and during the process of fixation by adding hydrochlorid acid caused precipitation of Prussian blue granules in the endolymphatic sac. From these experiments he suggested the "longitudinal-flow theory" where endolymph is assumed to be produced by stria vascularis in the cochlear duct and flows via the saccule into the endolymphatic sac

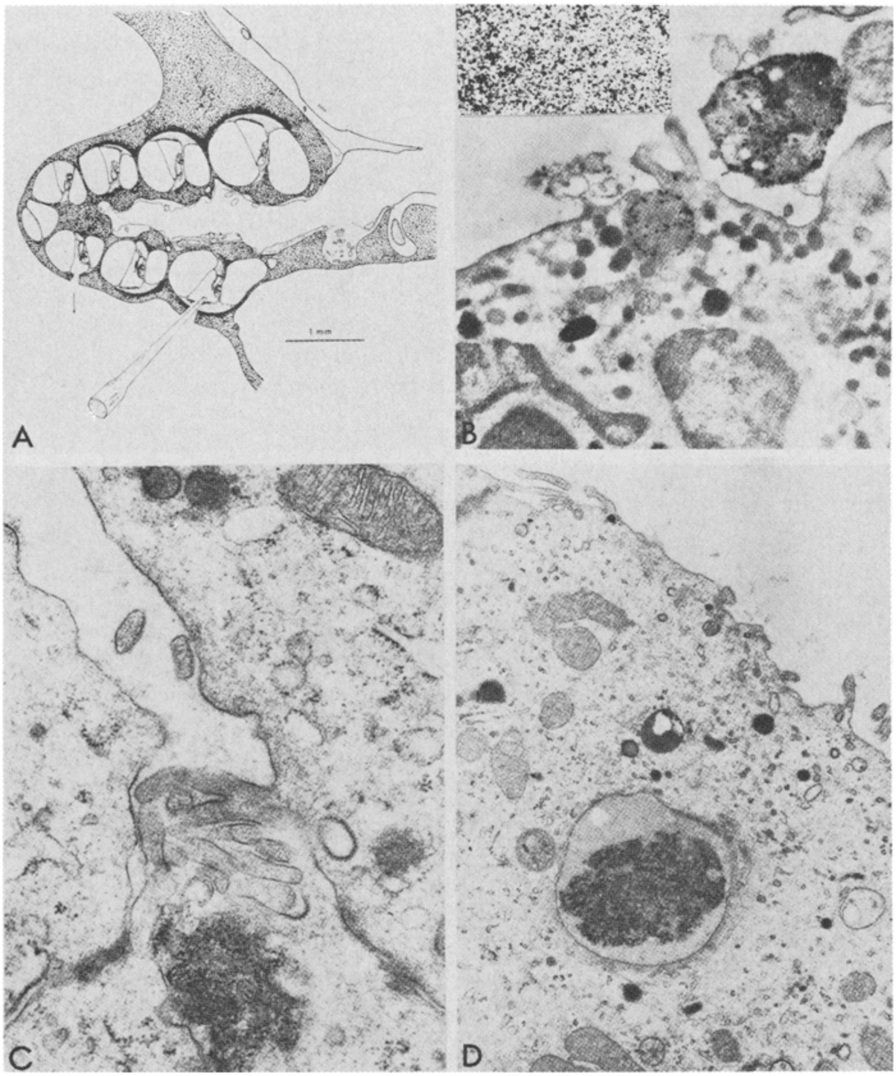

Fig. 5. A With microinjection of colloidal silver in the cochlear duct a marked activity can be induced in the endolymphatic sac. **B** Insert demonstrates size of colloidal silver particles which can be seen engulfed by free-floating macrophages in the main picture. **C** The dark cells of the intermediate part of the sac exhibits an active phagocytotic activity. **D** Silver particles present inside dark cell. (B, C, D, electron microscopy)

where it is resorbed. This suggestion of endolymph flow has been contradicted by Naftalin and Harrison (1958), Lawrence et al. (1961), and others who instead advocated the "radial-flow theory" where endolymph instead is locally produced in all regions where secretory cells are present. The necessary metabolic exchange for maintaining the sensory cell function is thus not related to the endolymphatic sac, but upheld locally.

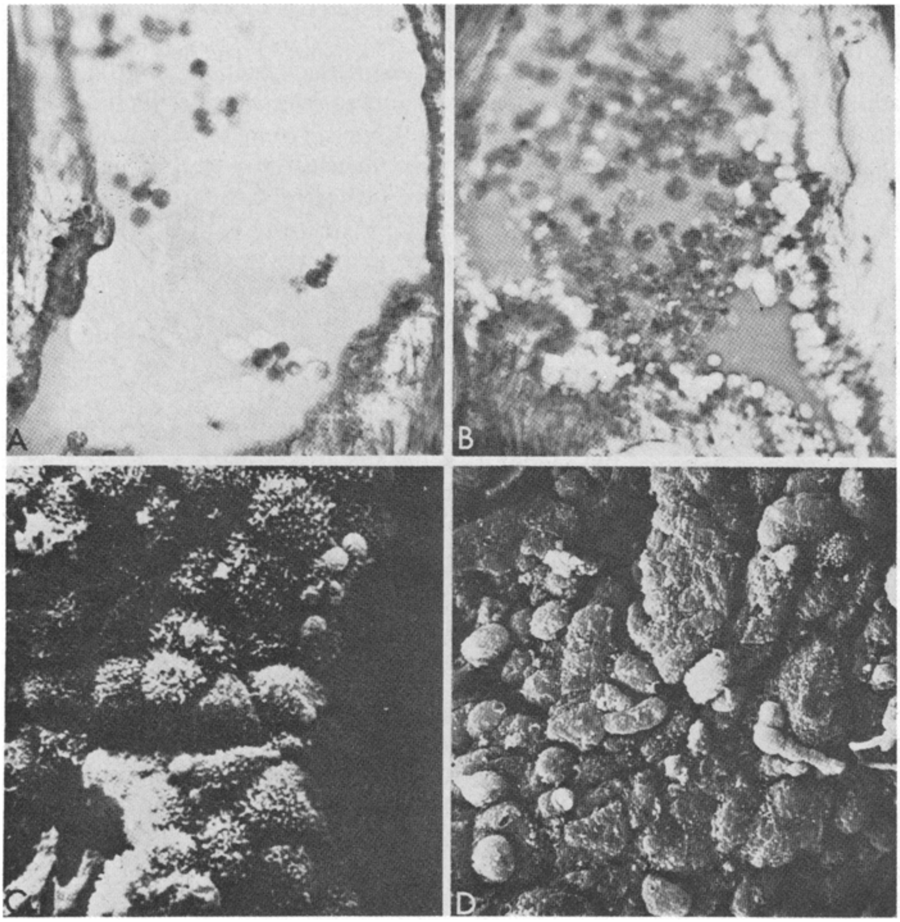

Fig. 6. In experiments with cryosurgery the lateral ampulla was destroyed. **A** Endolymphatic sac on control side. **B** Endolymphatic sac on operated side two days after surgery. Note the abundant cells and debris in the lumen of the sac as well as the irregular appearance of its epithelial lining. **C** Control side as seen with scanning electron microscopy. **D** Operated side, part where scanning electron microscopy demonstrates cells and debris attached to the epithelial surface of the intermediate portion of the sac

The experiments by Guild has been repeated by other investigators with the same result. With electron microscopy Lundquist and coworkers (1964, 1965) detailed the activity in the endolymphatic sac as follows:

Injection of colloidal silver particles in the cochlear duct demonstrated an accumulation of these inside the lumen of the endolymphatic sac after approximately 24 h. An active uptake of the particles was then found by the dark cells. These particles were traced inside the cells and were later found to be expelled into the histiocytes of the connective tissue beneath (Fig. 5). Similar experiments with live bacteria gave the same result. Careful experiments by Schuknecht and Kimura (1967) with blocking of the endolymphatic duct gave raise to a pronounced hydrops in the guinea pig labyrinth also suggestive of a reabsorptive capacity of the endolymphatic sac.

Late experiments by Lundquist and coworkers (Schindler et al., 1974; Lundquist et al., 1975) where cryosurgery was used as a tool to selectively destruct the lateral ampulla from the outside, without opening the bony labyrinth, also demonstrated a pronounced activity in the endolymphatic sac. Signs of an increased pinocytotic activity were found together with an increased number of free floating cells in the lumen of the sac 2—4 days after the surgically induced trauma. This demonstrates the capability of the sac to react in labyrinthine trauma (Fig. 6).

Comments

The briefly related experiments above clearly demonstrate that the endolymphatic sac can reabsorb fluid and phagocytose cellular debris and particles introduced in the labyrinth. The blocking of the endolymphatic duct also gives rise to an "endolymphatic hydrops" with a marked distention of the endolymphatic compartment as observed with histological techniques. Thus the endolymphatic sac must be involved in maintenance of endolymph equilibrium.

The Role of the Endolymphatic Sac in Endolymph Circulation

It was said by Lundquist 1965 that "experimental and morphological evidence indicate that the main function of the endolymphatic sac is to act as a reabsorptive and a defensive mechanism for the inner ear". Later experiments as related above also supports this theory. The question is then whether the experiments supporting the *radial-flow theory* or the experiments supporting the *longitudinal-flow theory* should be considered as valid.

If one however considers these two conflicting concepts from different standpoints it is possible to reach an agreement. Secretory cells are present around almost all sensory cell areas in the labyrinth (Kimura, 1969) and from a metabolic standpoint it seems reasonable to presume that the energy necessary for maintaining sensory cell function should be derived locally. The active ion exchange to keep the remarkably high level of potassium ions in the endolymph fluid could only be explained by a local *radial-flow*. However, as suggested by Lundquist (1967) this does not exclude a slow movement of endolymph towards the endolymphatic sac which in its role as a phagocytotic and reabsorptive part of the labyrinth can remove cellular debris and high molecular waste products from the endolymph circulation. The blocking of the endolymphatic duct also clearly suggests the endolymphatic sac to maintain fluid equilibrium in the labyrinth. The role of the endolymphatic sac in the Menière's disease is not clear. The descriptions of the epithelial lining of the sac as well as of its connective tissue in temporal bones of Menière's patients (Arenberg et al., 1970; Zechner, 1973) where a marked fibrosis of the sac is said to be present, also can be taken as signs of the importance of a normally functioning endolymphatic sac in maintaining fluid equilibrium in the labyrinth.

Instead of the two controversial theories regarding endolymph circulation, a "*dynamic-flow theory*" could be introduced and summarized as follows:

Dynamic-flow theory

Radial-flow	*Longitudinal-flow*
energy metabolism	reabsorption of endolymph
ion exchange	disposal of waist products

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Diskussionsbemerkungen

H. Spoendlin (Zürich): Verstand ich Sie richtig, wenn Sie schließen, daß im Saccusepithel hauptsächlich resorptive Funktion vorherrscht, denn wir haben ja dieselbe Situation auch im Bereich der dunklen Zellen der Crista ampularis.

P.-G. Lundquist (Stockholm): Nein, das meine ich nicht. Ich glaube, daß Zelldetritus (experimentell hervorgerufen durch Cryochirurgie oder ähnliche Eingriffe) von den Saccusepithelzellen phagozytiert werden können. Phagozytose gibt es natürlich unter solchen Bedingungen an verschiedenen Orten des Innenohres.

G. F. Dohlman (Gäddviksholm): Spritzt man Thorotrast in verschiedene Lymphräume des Innenohres ein, so wird man finden, daß alle Zellen zur Phagozytose der Thorotrastpartikelchen in der Lage sind, mit Ausnahme der dunklen Zellen. Diese scheinen den Fremdkörper geradezu abzustoßen, so ist es zumindest bei der Taube.

J. Angell-James (Bristol): Es gibt Untersuchungen aus Oxford, die zeigten, daß bei der Überprüfung der metabolischen Aktivität der Reißnerschen Membran die Sauerstoffaufnahme der Epithelzellen der Reißnerschen Membran größer war als in allen vergleichbaren Körpergeweben einschließlich der Niere und des Plexus chorioideus. Und hier liegen ja gerade die Natrium-Kalium-Pumpen, welche die entscheidenden Faktoren für den Elektrolyttransport zwischen Endo- und Perilymphe darstellen.

P.-G. Lundquist (Stockholm), Schlußwort: Man muß zusammenfassend sagen, daß überall im Endolymphraum Möglichkeiten der lokalen Resorption und Phagozytose vorhanden sind. Der Saccus scheint mehr eine Art Sicherheits- oder Ersatzorgan zu sein. Für den Energiemetabolismus und den Ionenaustausch muß eine radiäre „Strömung" der Endolymphe vorausgesetzt werden, für den Abtransport von Zelldebris (Phagozytose) und die Reabsorption der Endolymphe ist wohl eine longitudinale Strömung wahrscheinlich.