ABSTRACT

Epithelia vary with respect to transepithelial permeability. In those that are considered "leaky", a large fraction of the passive transepithelial flux appears to follow the paracellular route, passing across the zonulae occludentes and moving down the intercellular clefts. In "tight" epithelia, the resistance of the paracellular pathway to passive flux is greatly increased. To see whether differences in the morphology of the zonula occludens could contribute to this variability in leakiness among epithelia, replicas of zonulae occludentes in freeze-fractured material from a variety of tight and leaky epithelia were examined. The junctions appear as a branching and anastomosing network of strands or grooves on the A and B membrane fracture faces, respectively. It was found that the zonula occludens from a "very leaky" epithelium, the proximal convoluted tubule of the mouse kidney, is extremely shallow in the apical-basal direction, consisting in most places of only one junctional strand. In contrast, the "very tight" frog urinary bladder exhibits a zonula occludens that is relatively deep (>0.5 µm) in the apical-basal direction, and consists of five or more interconnected junctional strands interposed between luminal and lateral membrane surfaces. Epithelia of intermediate permeabilities exhibited junctions with intermediate or variable morphology. Toad urinary bladder, mouse stomach, jejunum, and distal tubule, rabbit gallbladder, and Necturus kidney and gallbladder were also examined, and the morphological data from these epithelia were compared to physiological data from the literature.

INTRODUCTION

Simple epithelia vary greatly in their ability to maintain ionic and osmotic gradients between physiological solutions of different compositions. Some, such as amphibian urinary bladders, do maintain steep gradients, while others, such as the fluid transporting gallbladder and the proximal convoluted tubule of the kidney, do not (Frömter and Diamond, 1972). Such leaky epithelia allow large amounts of water and small solutes to flow passively from one face of the epithelium to the other. Because of the relatively low permeability of the epithelial cell plasma membranes, a large fraction of the transepithelial flux moves between the cells, rather than through them (Frizzell and Schultz, 1972; Frömter, 1972), taking the paracellular shunt (Boulpaep, 1971). To follow this paracellular route, molecules at the epithelial free surface must cross the sealing junctions between the cells (the zonulae occludentes or tight junctions), and move along the intercellular clefts. Macromolecular tracer studies (Miller, 1960; Farquhar and Palade, 1963; Goodenough and Revel, 1970) indicate that the zonula occludens is an important barrier in the paracellular route, although some studies indicate that in leaky epithelia ionic lanthanum may penetrate the...
## Table I

Several Simple Epithelia Classified According to Transepithelial Resistance with Measurements of Junctional Morphology

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Transepithelial resistance in Ω cm⁻¹</th>
<th>Junctional Morphology</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No. of strands</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Depth in μm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Range</td>
<td>Mean ± SE</td>
<td>Range</td>
</tr>
<tr>
<td><strong>Very leaky</strong>—Mammalian proximal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>convoluted tubule</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dog</td>
<td>6 (5)</td>
<td>1-2</td>
<td>1.19 ± 0.12</td>
<td>*</td>
</tr>
<tr>
<td>Rat</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mouse</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Leaky—Necturus proximal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>convoluted tubule</td>
<td>70 (5)</td>
<td>1-6</td>
<td>3.3 ± 0.15</td>
<td>0.1-0.8</td>
</tr>
<tr>
<td>Rabbit gallbladder</td>
<td>30 (18)</td>
<td>2-6</td>
<td>4.1 ± 0.11</td>
<td>0.1-1.0</td>
</tr>
<tr>
<td><strong>Intermediate</strong>—Necturus gallbladder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>300 (17)</td>
<td>4-8</td>
<td>6.2 ± 0.21‡</td>
</tr>
<tr>
<td>Rat jejunum</td>
<td></td>
<td>&gt;300 (2)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Mouse jejunum</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Intermediate to tight</strong>—Distal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>convoluted tubule</td>
<td>300-600 (5)</td>
<td>4-7</td>
<td>5.3 ± 0.17</td>
<td>0.25-0.75</td>
</tr>
<tr>
<td>Necturus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mouse</td>
<td></td>
<td>4-7</td>
<td>5.9 ± 0.20</td>
<td>0.1-0.2</td>
</tr>
<tr>
<td><strong>Very tight</strong>—Mouse stomach</td>
<td></td>
<td>4-11</td>
<td>8.1 ± 0.34</td>
<td>0.3-0.9</td>
</tr>
<tr>
<td>Amphibian urinary bladder</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toad</td>
<td>1,000-2,000 (8)</td>
<td>5-11</td>
<td>8.1 ± 0.94</td>
<td>0.3-0.5</td>
</tr>
<tr>
<td>Frog</td>
<td></td>
<td>5-14</td>
<td>7.9 ± 0.38</td>
<td>0.3-1.1</td>
</tr>
</tbody>
</table>

*In most places the total junctional depth was equal to the width of one strand only.

‡ A. J. Hudspeth and A. G. Yee, personal communication.

§ Corrected for mucosal-serosal surface amplification (see Discussion).

N, number of measurements made (see Materials and Methods).

SE, Standard error of the mean.

The numbers in parentheses indicate the articles from which the physiological data were taken.

We have examined zonulae occcludentes in freeze-fractured material from a variety of tight and leaky epithelia and find that there are conspicuous and systematic differences in the depth and complexity of the junctions. These differences may be important in determining transepithelial permeability. A preliminary report of this work has appeared elsewhere (Claude and Goodenough, 1972).

### Materials and Methods

Specimens included mouse kidney, stomach, and jejunum, rabbit gallbladder, Necturus kidney, and gallbladder, frog (Rana pipiens) urinary bladder, and toad (Bufo marinus) urinary bladder. The kidneys were fixed by perfusion and then excised, and pieces were immersed in fixative. The other tissues were generally exposed to fixative in situ before pieces were

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measurements were made every 0.5 µm. Measurements
were not made in regions where more than two cells
come together, and the zonula occludens extends
farther basally than usual. For each epithelium, data
from all the micrographs were pooled and means
and standard errors of the means were calculated.

OBSERVATIONS

This study of the zonulae occludentes from various
epithelia has revealed a qualitative correlation be-
tween junctional anatomy and permeability. The
omenclature system used in this paper, based on
a survey of the physiological literature, classifies
the epithelia as “very leaky”, “leaky”, “inter-
mediate”, “tight”, or “very tight” on the basis of
transepithelial permeability (Table I). The most
dramatic morphological differences are seen be-
tween zonulae occludentes from very tight epithe-
lias such as frog and toad urinary bladders (specific
transepithelial resistance = 1,000–3,000 Ω cm²)
and zonulae occludentes from very leaky epithelia
such as the mammalian proximal convoluted tu-
bule (6 Ω cm²). Epithelia of intermediate perme-
abilities have zonulae occludentes of interme-
diate or variable morphology.

Fig. 1 shows a replica from frog urinary bladder and
illustrates the typical features of a tight zonula occludens. The junction itself is quite deep in the
apical-basal direction (0.5 µm or more) and is
composed of many (more than five) layers of inter-
connected strands interposed between lumen and
intercellular space. The junction appears as a net-
work of raised ridges on the A fracture face (inner
membrane leaflet) as is illustrated in Figs. 1, 2,
and 3, and as a series of interconnected grooves
on the complementary B fracture face (outer
membrane leaflet), illustrated in Figs. 2 and 3.
These two fracture faces have been shown to be
CLAUDE AND GOODENOUGH  "Tight" and "Leaky" Zonulae Occcludentes  393
complementary by the double replica technique and hence are the result of a single fracture plane. As described by Staehelin et al. (1969), the zonula occludens may take exceptionally long basal excursions in areas where more than two cells are joined; this phenomenon is illustrated in Fig. 2 (large arrow). Figs. 2 and 3, illustrating replicas from toad bladder and mouse stomach, respectively, are additional examples of physiologically tight epithelia. The zonulae occludentes are deep and display a complex morphology of at least five layers of interconnecting strands.

In sharp contrast to tight zonulae occludentes, the very leaky mouse proximal convoluted tubule displays an attenuated zonula occludens composed of only one or two strands. Figs. 4 and 5 show examples of zonulae occludentes from this epithelium. The junction in Fig. 4 is seen on both the A and B fracture faces; in Fig. 5, only the B face is evident. On the B face the junctional grooves are frequently studded with particles (Fig. 5, arrows); these particles may well represent remnants of the A face ridge still adhering to the B face, explaining the apparent discontinuities in some A face images (Fig. 4, heavy arrows).

These differences in junctional morphology do not simply reflect species differences. The tight (300-600 Ω cm²) mouse distal tubule zonulae occludentes (Fig. 6) may be contrasted with the junctions of the leaky mouse proximal tubule (Figs. 4 and 5). The distal tubule displays a zonula occludens with four or five interconnected strands and an overall depth of 0.1-0.2 μm. Proximal and distal tubule junctions from Necturus kidney may also be compared: the leaky (70 Ω cm²) proximal tubule junctions (Fig. 7) have two or three strands, with occasional interrupted strands (arrows), while the tight (300-600 Ω cm²) Necturus distal tubule junctions (Fig. 8) have four or five strands and a more complex branching and anastomosing network.

An interesting variation was seen in the rabbit gallbladder. This epithelium may be physiologically characterized as leaky (30 Ω cm²), yet some freeze-fractured replicas reveal a zonula occludens with an apparent tight morphology. As seen in Fig. 9, the rabbit gallbladder zonula occludens displays areas of many branching and anastomosing strands, with a deep apical-basal span. On close inspection, however, one can frequently find areas where the junction is reduced to only two or three strands (see arrows, Figs. 9 and 10). These latter areas may explain the physiological leakiness of the rabbit gallbladder.

Along the lateral surfaces of some epithelial cells one may encounter replicas of what appear to be elements of the zonula occludens. Branching and anastomosing ridges may be seen (arrows) which are not organized into true zonulae, and which are described better as maculae occludentes. Since these junctional elements are discontinuous, they do not contribute significantly to the total transepithelial resistance. The maculae occludentes have no known function, but may be related to the genesis or degradation of the zonula occludens.

**DISCUSSION**

In this survey we have seen that tight and leaky freeze-fractured zonulae occludentes differ in ultra-

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**FIGURE 4** Mouse proximal convoluted tubule, a very leaky epithelium. In most places the zonula occludens consists of only one strand, but there are occasional restricted areas where there are two or three strands. The junction is seen in both the A and B fracture faces. The heavy arrows indicate areas where pieces of the ridge appear to have broken away. Longitudinally fractured microvilli are seen in the upper part of the micrograph. Bar, 0.1 μm. X 70,000.

**FIGURE 5** Mouse proximal convoluted tubule. Zonula occludens seen in the B fracture face. There are numerous particles lying in the groove (arrows), perhaps having broken from the complementary fracture face during cleavage. Bar, 0.1 μm. X 105,000.

**FIGURE 6** Mouse distal convoluted tubule, a tight epithelium. The zonula occludens is deeper than in the proximal tubule and is composed of several (four or more) anastomosing strands, here seen as grooves in the B fracture face. Bar, 0.1 μm. X 70,000.
"Tight" and "Leaky" Zonulae Occludentes
Figure 7 Necturus proximal convoluted tubule, a leaky epithelium. Some of the strands in the zonula occludens are discontinuous (arrows). In places it looks as though portions of the ridges on the A fracture face are broken away, revealing grooves underneath (asterisks). Bar, 0.1 µm. × 68,000.

Figure 8 Necturus distal convoluted tubule, a tight epithelium. The zonula occludens, here seen in the B fracture face is deeper and more complex than in the proximal tubule. Bar, 0.1 µm. × 120,000.

Figure 9 Rabbit gallbladder, a leaky epithelium. In some places the zonula occludens is quite deep (>0.5 µm) and is composed of several strands. However, there are also areas (heavy arrows) where the junction is shallower and consists of only two or three strands; these attenuated areas may provide a favorable route for the transepithelial flow of ions. Bar, 0.5 µm. × 43,500.
FIGURE 10 Rabbit gallbladder, a leaky epithelium. This is another example of a region of the zonula occludens where overall junctional depth is reduced (arrows) and there are only two to three strands making up the junction. Bar, 0.1 μm. × 64,000.

FIGURE 11 Mouse stomach, the lateral surface of an epithelial cell. As well as frequent small gap junctions, there are occasional anastomosing ridges that resemble elements of the zonula occludens, but are not associated with it. Since they are discontinuous, they do not contribute significantly to paracellular transepithelial resistance. Bar, 0.5 μm. × 55,000.
structure; very tight epithelia have deep zonulae with a complex network of anastomosing strands, while very leaky epithelia have shallower junctions composed of fewer strands. Epithelia with intermediate permeabilities generally have zonulae with intermediate, or variable morphology.

In comparing the data from different tissues as it is expressed in Table I, we can see that transepithelial permeability is correlated more closely to the number of strands that make up the junction than it is to total junctional depth. This is particularly evident in mouse distal tubule, where the zonula is made up of five or six strands which are compressed into a band less than 0.25 µm in depth, and in the toad urinary bladder, where approximately eight strands are compressed into 0.4 µm or less. If the tissues are grouped according to junctional morphology, the mouse stomach and the amphibian urinary bladders fall into one very tight category, with about eight strands, and the mouse proximal tubule represents the other extreme, very leaky, with only one strand in most places. *Necturus* proximal tubule and rabbit gallbladder look "fairly leaky", with three or four strands making up the zonula occludens, while *Necturus* distal tubule and gallbladder and mouse distal tubule could be grouped together as having a "fairly tight" morphology with five or six strands. Because the junctions can be quite variable in some tissues, such as the rabbit gallbladder, and because of difficulties inherent in making both the morphological and physiological measurements (see below), it seems premature at this time to try to make the correlations more precisely than this.

We found it advantageous to use freeze-fractured material rather than thin sections for two reasons. Although the difference in junctional depth between tight and leaky epithelia can often be quite striking in sectioned material (Farquhar and Palade, 1963; Claude, 1966, 1968), there is still the problem of orientation; an oblique section through a junction will make it appear deeper than it really is. This difficulty does not arise in freeze-fractured material. Another advantage of the technique is that the anastomosing strands that make up the junction are clearly visible. These strands, seen as ridges or as grooves in the A or B fracture faces, may be the intramembrane counterpart of the focal contacts (kisses) that are occasionally resolved in thin sections. Goodenough and Revel (1970) have presented negative-stain evidence that this branching and anastomosing network reflects the pattern of functional membrane contacts within the zonula occludens, and hence the site of the transepithelial permeability seal to macromolecular tracers such as hemoglobin (Miller, 1960; Farquhar and Palade, 1963). Our present results indicate that the number of strands, or barriers, in a junction and their geometrical arrangement may be more important to junctional permeability than overall junctional depth, so it is important to be able to resolve the individual strands; the freeze-fracture technique is ideal for this.

Current interpretations of freeze-fractured cell membranes (Branton, 1966; Pinto da Silva and Branton, 1970) postulate a splitting of the membrane in its hydrophobic interior. Thus the strands that appear in freeze-fractured zonulae occludentes probably represent structures lying within the junctional membranes rather than representing structures between the two membrane outer leaflets where they appear to fuse.

Additional resistances in the paracellular pathway must be accounted for in an attempt to correlate junctional morphology to transepithelial permeability. In some cases the interspaces basal to the zonula occludentes are long and narrow enough to account for an appreciable part of the total resistance of the paracellular pathway. This situation arises in fairly leaky epithelia where junctional permeability is high and where the cells are tall and in close apposition to one another (Claude, 1968; Smulders et al., 1972; Wright et al., 1972). In epithelia where the junctions are very tight, however, the permeability of the paracellular pathway is reduced, and more of the flux is forced to pass through the cells. In these situations, the overall transepithelial permeability will tend to reflect the properties of the epithelial cell membranes, rather than properties of the paracellular pathway.

There are geometrical factors that will affect the contribution of the paracellular pathway to total transepithelial flux. The overall resistance of the paracellular pathway will depend not only on its specific resistance in the transepithelial direction, which will be determined by its structure, but also on the amount of this pathway available per unit area of luminal surface. Thus, although two epithelia may have junctions and intercellular clefts with the same specific resistance, the total flux carried by the paracellular shunt will be greater in the epithelium with more junctional element and intercellular cleft per unit area of luminal surface. For example, an epithelium made
up of small cells will have more zonula occludens per unit area of luminal surface than an epithelium with larger cells. Similarly, if there is much interdigitation between cells at the level of the junction, there will be more junction available per unit area of luminal surface.

A related geometrical problem also exists in epithelia where there is a large difference in surface area between serosa and mucosa. In the small intestine, for instance, the mucosal surface area may be an order of magnitude greater than the serosal surface area because of the villi (Wilson, 1962; Barry et al., 1965). The true mucosal transepithelial permeability would therefore be an order of magnitude lower than that calculated on the basis of serosal surface area alone (see Table I).

It is important to recognize that measurements of transepithelial flux represent the average flux per unit area, and do not reflect local variations in permeability. If the junctions are tight in some places and leaky in others, the measured permeability will be the sum of all the local permeabilities. This situation may exist in the rabbit gallbladder, where junctional morphology appears quite variable. Local variations may also arise where different cell types occur in a single epithelium. Examples may be found in the gastric mucosa, the small intestine, and in the proximal convoluted tubule of Necturus (Chase, 1923; Claude, 1967). Transient leaks may develop across epithelia such as the intestinal mucosa, where the rapid rate of cell turnover results in the sloughing off of cells with a concomitant breaking and rejoicing of the zonula occludentes.

As in any fine structural analysis, we are limited by the resolution of electron microscope techniques. Junctions from different epithelium may have different permeabilities based on variations in the ionic composition or degree of hydration of the junctional strands, even though they may not appear different in the electron microscope. These differences may be defined by chemical means or by studying the ion selectivity of the paracellular pathway (Barry et al., 1971; Machen and Diamond, 1972). In addition, it is possible that differences in permeability exist between strands in a single junction. Evidence suggestive of this has been obtained from osmotically stressed toad bladders where the zonula occludens responds asymmetrically to osmotic gradients (DiBona, 1972; Wade et al., 1973).

In conclusion, it appears possible to relate the morphology of the zonula occludens qualitatively to its transepithelial permeability. However, quantitative comparisons must depend on a careful assessment of all the possible geometrical and chemical variations that affect measurements of transepithelial permeability.

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