ZO-3, a Novel Member of the MAGUK Protein Family
Found at the Tight Junction, Interacts with ZO-1 and Occludin

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Abstract. A 130-kD protein that coimmunoprecipitates with the tight junction protein ZO-1 was bulk purified from Madin-Darby canine kidney (MDCK) cells and subjected to partial endopeptidase digestion and amino acid sequencing. A resulting 19-amino acid sequence provided the basis for screening canine cDNA libraries. Five overlapping clones contained a single open reading frame of 2,694 bp coding for a protein of 898 amino acids with a predicted molecular mass of 98,414 daltons. Sequence analysis showed that this protein contains three PSD-95/SAP90, discs-large, ZO-1 homology (SH3) domains, a src homology (SH3) domain, and a region similar to guanylate kinase, making it homologous to ZO-1, ZO-2, the discs large tumor suppressor gene product of Drosophila, and other members of the MAGUK family of proteins. Like ZO-1 and ZO-2, the novel protein contains a COOH-terminal acidic domain and a basic region between the first and second PDZ domains. Unlike ZO-1 and ZO-2, this protein displays a proline-rich region between PDZ2 and PDZ3 and apparently contains no alternatively spliced domain. MDCK cells stably transfected with an epitope-tagged construct expressed the exogenous polypeptide at an apparent molecular mass of ~130 kD. Moreover, this protein colocalized with ZO-1 at tight junctions by immunofluorescence and immunoelectron microscopy. In vitro affinity analyses demonstrated that recombinant 130-kD protein directly interacts with ZO-1 and the cytoplasmic domain of occludin, but not with ZO-2. We propose that this protein be named ZO-3.

The tight junction acts to limit movement of substances through the paracellular space and as a boundary between the compositionally distinct apical and basolateral plasma membrane domains of epithelial and endothelial cells. The molecular configuration of the tight junction has generated considerable interest in the last decade. Actin filaments (17, 29) and the peripheral membrane proteins ZO-1 (40), cingulin (10), ZO-2 (21), 7H6 (48), Rab3B (43), symplekin (22), and AF-6 (47) are now known to be found at the tight junction. Occludin, a transmembrane protein, is also localized to the tight junction (14). Limited information is available on the roles these elements play in tight junction physiology. For example, actin filaments are believed to function in the regulation of junction permeability (30), although the molecular linkage by which this occurs is unknown. Data from several laboratories indicate that occludin functions as part of the paracellular permeability barrier (6, 31, 45) and participates in intercellular adhesion (42); however, it remains possible that other, unidentified transmembrane components may also be involved.

ZO-1 and ZO-2 were among the first tight junction proteins identified (16, 21, 40). Cloning and sequence analysis of these proteins indicates that they are part of a larger family of proteins potentially involved in tumor suppression and/or signal transduction (21, 44). This family includes the disc large tumor suppressor gene product (dlg-A) of Drosophila (46); p55, an erythrocyte membrane protein (35); and PSD-95/SAP90, a synaptic membrane protein (9, 25). TamA, a second Drosophila protein homologous to ZO-1, has also been identified (41). Common to all family members is a region homologous to guanylate kinase (GUK)1, an src homology (SH3) domain, and variable numbers of PDZ domains. These latter domains have been shown to function in binding integral membrane proteins such as ion channels at synapses (23, 27). In addition, the GUK domain of PSD95/SAP90 has been shown to bind a novel synaptic protein (24), and the SH3 domain of ZO-1 binds a serine protein kinase that phosphorylates a region at the COOH-terminal end of the protein (4). The membrane association and presence of GUK domains in this collection of proteins has resulted in their being named the MAGUK family (1).

Information on direct interactions among tight junctional proteins is also limited. Affinity analyses indicate

1. Abbreviations used in this paper: aa, amino acid; GUK, guanylate kinase; PVDF, polyvinylidene difluoride; SH3, src homology; VSV-G, vesicular stomatitis virus G protein.
that ZO-1 binds to occludin (15) and the Ras target AF-6 (47). Additional observations suggest that ZO-1 has the capacity to bind spectrin (15, 20), although localization of this cytoskeletal protein to the tight junction has not been documented. These observations, together with the protein-binding capacities of the MAGUK domains, make it likely that the tight junction conforms to the architectural paradigm of the adherens junction and desmosome, that of transmembrane constituents linked to the cytoskeleton through a complex of peripheral membrane proteins.

Immunoprecipitation of ZO-1 performed under conditions designed to preserve protein–protein interactions indicates that an additional protein at 130 kD interacts with a complex containing ZO-1 and ZO-2 (5). Although this protein is known to be phosphorylated, it has not been further characterized to date. Here we report the isolation, identification, and partial characterization of the 130-kD protein. We find this protein to be a novel member of the MAGUK protein family that directly interacts with ZO-1 and occludin. As the protein localizes to the tight junction (zonula occludens), we name it ZO-3.

Materials and Methods

Cell Culture

MDCK strain II cells were grown and metabolically labeled as described previously (2, 37). The MDCK cell line MDCK/Z3 was generated by transfection of the parental line with a full-length ZO-3 construct in pBK-CMV (see below) using Lipofect (GIBCO BRL, Gaithersburg, MD) and G418 selection according to established protocols (3). Passage and growth of MDCK/Z3 cells were identical to that of parental cells. S9 in situ cells (GIBCO BRL) were grown in serum-free medium (Sf-900 II SFM; GIBCO BRL) at 28°C in a nonhumidified, ambient air incubator on an orbital platform rotating at 125 rpm. The cell density was maintained between 4 × 10^5 to 2 × 10^6 cells/ml with viability >90%.

Immunoprecipitation

Immunoprecipitations under conditions that maintain some protein-protein interactions ("low stringency") were performed by a modification of previously published techniques (16, 21). Confluent monolayers of MDCK cells were rinsed twice in ice-cold TBS with 1 mM CaCl_2, 0.5 mM MgCl_2, 0.2 mM PMSF, and 1 μg/ml aprotinin. Cells were solubilized in 1% Triton X-100, 0.5% sodium deoxycholate, 0.2% SDS, 150 mM NaCl, 20 mM Hepes, pH 7.4, 2 mM EDTA, 1 μg/ml aprotinin, 0.2 mM PMSF, 1 μg/ml chymostatin, 1 μg/ml leupeptin, and 1 μg/ml pepstatin. Solubilized material was centrifuged at 13,000 g for 30 min at 4°C to remove cell debris. Rat anti-ZO-1 mAb R40.76 (2) was added to the supernatant, followed by goat anti-rabbit IgG (Jackson ImmunoResearch Laboratories, Inc., West Grove, PA) coupled to cyanogen-bromide–activated Sepharose 4B (Pharmacia Biotech, Inc., Piscataway, NJ). As a negative control, R521, a rat mAb identical in isotype to R40.76(40), was used. Sepharose beads were washed according to procedures of Pasdar and Nelson (1989) and solubilized in gel sample buffer.

High stringency immunoprecipitations of ZO-1, ZO-2, and ZO-3 (tagged with an 11–amino acid epitope from the cytoplasmic domain of vesicular stomatitis virus G protein [VSV-G; see below]) from cells solubilized in hot 1% SDS were done as described previously (39) using R40.76 anti-ZO-1/anti-rabbit IgG–Sepharose, rabbit polyclonal anti-ZO-2 (reference 21; R9899, a gift from Lynne Jesuitis and Dan Goodenough, Harvard Medical School, Boston, MA)/protein A–Sepharose (Pharmacia Biotech, Inc.), and a mouse anti-VSV-G cytoplasmic domain mAb (clone P5D4; Boehringer Mannheim Corp., Indianapolis, IN)/protein G–Sepharose (Pharmacia Biotech, Inc.).

Isolation and Cloning of ZO-3

Bulk Immunoprecipitation and Purification. ZO-1 was immunoprecipitated from 104 roller bottles (1,600 cm² each) of MDCK cells under low stringency conditions. Immunoprecipitates solubilized in gel sample buffer were pooled, concentrated by centrifugation in filter concentrators (Centriprep 100; Amicon Corp., Danvers, MA) and run on preparative SDS-PAGE. Approximately 25 μg of ZO-3 (determined by comparison of Coomassie blue-stained standards) were transferred onto PVDF in a Hoeffer TE42 transfer apparatus operated at 90 volts for 6 h and maintained at 20°C by a temperature controlled water bath. Transfer buffer (25 mM Tris, pH 8.3, 190 mM glycine, 0.01% SDS) was changed after 4 h. Protein on the polyvinylidene difluoride (PVDF) was visualized by staining with amido black. Buffer and transfer conditions were optimized for ZO-3 by test transfers with metabolically labeled material.

Amino Acid Sequencing and RT-PCR. The PVDF containing ZO-3 was submitted to the Rockefeller University Protein Sequencing Facility for Lys-C endopeptidase microdigestion (12) and amino acid (aa) sequencing. We followed the modified 19-aa sequence: TGGVL4TGN=RTDN. Degenerate primers corresponding to the 6 aa at each end were synthesized: forward, 5'-AC(AC) GC(C)TAG ATG CC(T) GA'-3'; reverse, 5'-TTT GTC (GT) GTC(T) CG(C) (GA) GC-3'. RT-PCR was performed with these primers on total RNA isolated from MDCK cells with TRIZOL (GIBCO BRL) according to manufacturer directions. PCR products were subcloned into the TA vector (Invitrogen Corp., Carlsbad, CA). The authenticity of the PCR products was verified on Southern blots using a degenerate synthetic oligonucleotide (5'-GA(C/T) CA(AG) GT(GT) AC(AT) CG-3') end-labeled with [γ-32P]ATP (ICN Pharmaceuticals Inc., Irvine, CA). This oligonucleotide corresponded to the internal aa of the original peptide. Positives on Southern blots were subjected to double-stranded sequencing. A 57-mer that verified the entirety of the original 19-aa peptide was obtained.

Library Screening. The 57-mer was synthesized, end labeled with [γ-32P]ATP, and used to screen an oriented oligo(dT)primed MDCK cell cDNA library in λ-ZAP (provided by Marino Zerial, European Molecular Biology Laboratory, Heidelberg, Germany) using the method of Ausubel et al. (1992). 10 positively hybridizing phage were isolated after screening ~500,000 plaques. plBluescript containing inserts were excised from plaque-purified phage as directed by the manufacturer (Stratagene, La Jolla, CA). The longest insert (A1, 1.6 kb) was subjected to double-stranded sequencing. Analysis of this sequence, together with the molecular mass of the protein and size of the mature ZO-3 mRNA determined by Northern blot (~3.4 kb, see Fig. 4), indicated that the A1 clone contained the 3' but not the 5' end of the open reading frame. To extend the 5' end of the ZO-3 sequence we constructed an oriented MDCK cDNA library specific for ZO-3 in Uni-ZAP XR (Stratagene). MDCK cell poly(A)+ RNA was isolated by PolyATract mRNA System III (Promega Corp., Madison, WI) and reverse transcribed with a ZO-3-specific antisense linker-primer (5'-GAG AGA GAG AGA GAG AGA GAA GTA CTC TCG AGC TGA TCT CCC TCC TCG AGT-3') containing an XhoI site. This primer was situated 173 bp downstream of the 5' end of clone A1. The cDNA was ligated with EcoRI adaptors, digested with XhoI, size fractionated, and ligated into the Uni-ZAP XR vector. The resulting library was screened with the oligonucleotide 5'-GAG CTA TGA CAT CTA CAG GTG GCC CAG CCA GGC AGG ABA CCG TG-3' end-labeled with [γ-32P]ATP. This sequence is the complement of a known region of the A1 clone located in the 173 bp 5' of the primer used to create the library. Approximately 200,000 plaques were screened and 6 positive clones plaque purified. Inserts were sized by restriction digestion and the 5' 200–300 bp were sequenced to verify the clones were ZO-3 specific. The longest clones were selected for double strand sequencing. All sequencing was performed through the use of Sequenase Version 2.0 (United States Biochemical Corp., Cleveland, OH). Fidelity DNA Sequencing System (Oncor, Inc., Gaithersburg, MD), or the University of Alberta DNA Sequencing Facility.

Sequence Analysis. Nucleotide sequences, aa compositions and isoelectric points of various domains, and the overall molecular mass of the protein were analyzed using the University of Wisconsin Genetics Computer Group (GCG) software package. Amino acid sequence comparisons to determine the percent identity and the percent similarity (percent identity + percent conserved substitutions) were done using the default parameters in the GCG GAP alignment program based on the algorithm of Needleman and Wunsch (1970). Sequence alignments were performed with GCG PILEUP. The amino acid numbers of compared sequences are shown in Table I.

Northern and Southern Blotting

Total RNA was isolated from MDCK cells for Northern blots by the one step protocol of Ausubel et al. (1992), and poly(A)+ mRNA was generated by the PolyATract System III (Promega Corp.). RNA was trans-
ferred to Magna (MSI) nylon membrane and cross-linked with UV radiation (Stratalinker; Stratagene). A 230-bp fragment at the 5' end of the ZO-3 A1 cDNA generated by EcoRI/PstI digestion (see Fig. 2) and an 880-bp fragment of ZO-2 generated by PCR (primers: forward, 5'-GGACGAGGAGCCGACG-3'; reverse, 5'-TCCTCTTCACTGCAGAT-3') were labeled by random-priming and used as probes. Blots were hybridized overnight at 68°C and washed according to previously published protocols (18). Southern blots were performed according to established procedures (3) using Duralon UV (Stratagene) and probed as described above.

**Epitope Tagging of ZO-3**

A full-length ZO-3 cDNA was assembled from overlapping clones and subcloned into the eukaryotic expression vector pBK-CMV (Stratagene). To remove the 241 bp 5' untranslated region of the ZO-3 cDNA, the 5' region was amplified by PCR with the following primers: forward, 5'-GGG AAT TCC AGG TGC TGG ACA TGG AGG A-3'; reverse 5'-CGG CAC CATCT GGA GAC CAC GAC C-3' (nucleotides 380–359 of Fig. 3). The forward primer contains an EcoRI restriction site and the 12 bp internal fragment was used to replace the original 5' end of ZO-3 by restriction digestion with EcoRI and XcmI (see Fig. 2). The COOH terminus of ZO-3 was tagged with the 11-aa VSV-G epitope by PCR using the following primers: reverse, 5'-GCA CAA TCT AGA TTA CTT CTT AAG-3'; reverse 5'-GCA GAG ACG GAC GGC GAG GG-3'. The amplified fragments were verified by DNA sequencing.

**Immunoblotting**

Immunoblots were performed using ECL (Amersham Corp., Arlington Heights, IL) according to manufacturer's protocols. Whole cell lysates were prepared according to Stevenson et al. (1994). The following primary antibodies were used: anti-ZO-1 mAb R40.76 (2); rabbit anti-ZO-2 (21); rabbit anti-VSV-G cytoplasmic domain (a gift from Carolyn Machamer, Johns Hopkins University, Baltimore, MD); an anti-human ZO-1 polyclonal antibody (Zymed Laboratories, Inc., South San Francisco, CA); and a partially characterized guinea pig antisera generated against a ZO-3 fusion protein corresponding to the linker region between PDZ1 and PDZ2 (aa 95–185). This anti-ZO-3 antisera shows strong reactivity to the fusion protein (data not shown), recombinant full-length ZO-3 and a 130-kD band present in whole MDCK cell lysate (see Fig. 9 c). However, it also shows faint reactivity on immunoblots of MDCK cell lysates with a band that comigrates with ZO-1. The nature of this reactivity has not been fully clarified but is irrelevant to the binding studies for which it was used (the antisera was not used for immunocalocalizations; see below). Peroxidase-conjugated goat anti-rat IgG, goat anti-guinea pig IgG (Jackson Immunoresearch Laboratories, Inc.) and goat anti-rabbit IgG (Bio-Rad Laboratories, Heracles, CA) were used as secondary antibodies.

**Localization of ZO-3**

Immunofluorescence was performed according to previously published protocols (18) using R40.76 anti-ZO-1 rat mAb/Pt/Ct-conjugated goat anti-rat IgG (Jackson Immunoresearch Laboratories, Inc.) and rabbit anti-VSV-G/ribosominium-conjugated donkey anti-rabbit IgG (Jackson Immunoresearch Laboratories, Inc.). MDCK/Z3 cells were fixed with 2.5% paraformaldehyde and permeabilized with ~20°C methanol before staining. ImmunoEM was performed on isolated MDCK/Z3 cell membranes according to the technique of Jesaitis and Goodenough (1994) except that membranes were fixed with 2.5% paraformaldehyde for 15 min on ice following quenching by 50 mM glycine, 1% BSA in PBS for 20 min on ice before antibody incubations. Membranes were then colabeled with R40.76 anti-ZO-1/10 nm gold-conjugated goat anti-rabbit (British BioCell International, Cardif, UK) and rabbit anti-VSV-G/5 nm gold-conjugated goat anti-rabbit (Sigma Chemical Co., St. Louis, MO) before processing for thin section EM (40).

**Affinity Binding**

**Protein Expression.** Full-length canine ZO-2 (7) and ZO-3 cDNAs were subcloned into the pFastBac HT vector series of the Baculovirus eukaryotic expression system (GIBCO BRL, Gaithersburg, MD). The resulting constructs (pHTb/ZO-2 or pHTc/ZO-3) encode proteins with a 6-histidine tag at the NH2 terminus. pHTb/ZO-2 and pHTc/ZO-3 were transformed into Escherichia coli DH10Bac cells containing the Baculovirus genome. DNA isolated from the transformed DH10Bac bacteria was transfected into Schneider insect cells using Lipofectamine. Transfected Sf9 cells were harvested at 48 h (ZO-2) or 60 h (ZO-3) after infection. Harvested cells were centrifuged at 500 g for 5 min and cell pellets were kept at ~70°C until needed. The parental vector pFastBac HTc alone (pHTc), coding for the 6-histidine tag plus 36 nonspecific aa, served as a negative control.

Full-length ZO-3 cDNA was also subcloned into prokaryotic expression vector pGEX-3X to generate GST/ZO-3 fusion protein. A cDNA encoding the cytoplasmic tail of ZO-2 was cloned into the pGEX-3X vector, generating GST/ZO-2. A cDNA encoding the VSV-G cytoplasmic domain (11-aa VSV-G epitope) was cloned into the pGEX-3X vector, generating GST/VSV-G. The GST fusion proteins were prepared according to manufacturer instruction (Pharmacia Biotech, Inc.). In brief, 50 ml of medium was inoculated with 5 ml of an overnight culture in the presence of 100 mg/ml ampicillin. The culture was incubated at 37°C for 10 h with shaking at 250 rpm followed by the addition of IPTG to a final concentration of 0.1 mM, and the incubation was continued for 3.0 h. Cells were harvested by centrifugation at 5,000 g for 10 min and re-suspended in 2 ml PBS containing 1.0 mM DTT, 1.0 mg/ml BSA, 1 mg/ml apronin, 0.2 mM PMSF, 1 mg/ml chymostatin, 1 mg/ml leupeptin, and 1 mg/ml pepstatin. Cells were sonicated briefly and then mixed with 10% Triton X-100 to a final concentration 1.0%. The cell lysate was clarified by centrifugation at 10,000 g for 30 min at 4°C to remove insoluble material. The supernatant was transferred to a new tube, mixed with 0.1 ml of a 1:1 slurry of glutathione/agarose (prewashed with PBS), and incubated for 30 min at room temperature. The beads were washed 4× 1.0 ml in cold PBS. Vector encoding GST alone served as a negative control.

Recombinant ZO-1 was prepared by in vitro transcription/translation according to manufacturer's instructions (Promega Corp.) from a full-length human ZO-1 cDNA subcloned into pBlueScript SK+ under control of T7 promoter (obtained from Drs. Anderson and Fanning). In brief, 25 ml TNT rabbit reticulocyte lysate, 2 l TNT reaction buffer, 1 l TNT T7 RNA polymerase, 1 l amino acid mixture minus methionine (1 mM), 40 U RNasin, 1 l template DNA, and 4 l [35S]methionine (1,000 Ci/mmol, 10 mM C125I/mol; ICN Pharmaceuticals Inc., Irvine, CA) were used for each reaction in a total volume of 50 l. The reaction mixtures were incubated at 30°C for 90 min and the protein product used immediately in binding assays.

**Indirect Binding.** Binding of recombinant ZO-3 to ZO-1 and ZO-2 from whole MDCK cell extracts was assayed according to modifications of the technique of Fusaro et al. (99). A cell pellet from a 50–ml culture of pHtC/ZO-2/S0 or pHtC/S0 cells was thawed on ice and resuspended in 2 l lysis buffer containing 50 mM NaH2PO4, 300 mM NaCl, 10 mM MgCl2, 10 mM imidazole, pH 8.0, 1 mg/ml apronin, 0.2 mM PMSF, 1 mg/ml chymostatin, 1 mg/ml leupeptin, and 1 mg/ml pepstatin. Lysozyme was added to a final concentration of 1 mg/ml. The cell suspension was incubated on ice for 30 min, at which time DNase was added to 5 mg/ml and
the suspension incubated on ice for another 15 min. After sonication, NP-40 was added to the cell lysate to a final concentration of 1%, and the mixture incubated at 4°C for 30 min to solubilize the over-expressed ZO-3 protein. The suspension was centrifuged at 10,000 g for 20 min and the pellet discarded. For each binding reaction, 50 μl of Probond beads (Invitrogen Corp.) were washed with 3 ml wash buffer. 500 μl of pH 7.5, 5 mM MgCl₂, 1 μg/ml aprotinin, 0.2 mM PMSF, 1 μg/ml chymotisin, 1 μg/ml leupetin, and 1 μg/ml pepstatin) and used for binding assays.

Confluent MDCK cells in 2 × 15-cm dishes were scraped, pelleted and homogenized in 5 ml solution K (140 mM KCl, 10 mM Hepes, pH 7.5, 1 mM MgCl₂, 1 μg/ml aprotinin, 0.2 mM PMSF, 1 μg/ml chymotatin, 1 μg/ml leupetin, and 1 μg/ml pepstatin) and used for binding assays.

The first clone obtained, A1, was subsequently used to screen the MDCK cDNA library. The clone demonstrated that the predicted aa sequence contains 3′ and 5′ untranslated regions. Open reading frame indicated by the box, with XcmI, Scalou, and XhoI restriction sites at the 5′ and 3′ ends. (Solid lines) Untranslated regions. Open reading frame indicated by the box, with XcmI, Eagl, PstI (unique to the A1 cDNA), and internal XhoI restriction sites. (b) Individual clones obtained from library screening. All partial cDNAs were subjected to double-stranded sequencing. (c) Scale bar in 1-kb segments.

**Results**

**ZO-3 Is a Member of the MAGUK Family**

Previous investigations showed that a protein of 130 kD specifically coimmunoprecipitates with ZO-1 and ZO-2 under conditions designed to preserve protein–protein interactions (5, 21). We repeated these observations and noted that the 130-kD protein is present in significantly smaller quantities than either ZO-1 or ZO-2 (Fig. 1). However, isolation by bulk immunoprecipitation and purification by gel electrophoresis provided enough of the 130-kD polypeptide for endopeptidase digestion (12) and aa sequencing. Degenerate primers based on the 6 aa at each end of a unique 19-aa fragment were synthesized, and RT-PCR from MDCK cell RNA generated a 57-bp oligonucleotide that confirmed the entire original 19 aa. This 57-mer was then used to screen a MDCK cDNA library. The first clone obtained, A1, was subsequently used to screen the same library. To obtain the 5′ end of the cDNA, an oriented MDCK cDNA library specific for the protein was created.

In all, five overlapping clones were obtained (Fig. 2). Sequencing shows that these cDNAs contain a single open reading frame of 2,694 bp coding for 898 aa (Fig. 3). The overall size of the cDNAs obtained (∼3.4 kb) corresponds well with the ∼3.4 kb mRNA for the protein detected by Northern blot (Fig. 4). The predicted molecular mass for this aa sequence is 98,414 D, indicating that the protein runs anomalously on SDS-PAGE, as previously observed for other proteins including ZO-1 and ZO-2 (21, 44), or is posttranslationally modified. The 130-kD protein was previously shown to be phosphorylated (5). Sequence analysis demonstrates that the predicted aa sequence contains 3 PDZ domains, an SH3 domain and a GUK region (Fig. 3), indicating homology to ZO-1, ZO-2, the gene products from Drosophila discs large (dlg-A) and tamou (TamA),...
and other MAGUK family members. Amino acid sequence comparisons of the MAGUK domains from ZO-1, ZO-2, ZO-3, TamA, and dlg-A illustrate that ZO-3 has a high degree of similarity to ZO-1 and ZO-2 in all three domains, as well as in overall sequence (Table II, Fig. 5). Furthermore, ZO-3 shows approximately the same level of similarity to dlg-A as ZO-1. However, ZO-3 and especially ZO-1 show higher degrees of similarity to TamA than to dlg-A, suggesting that TamA is the closer Drosophila family member. We conclude that ZO-3 is a novel member of the MAGUK family of proteins.

In addition to the MAGUK domains, ZO-3 shares with ZO-1 and ZO-2 the presence of a basic domain between PDZ1 and PDZ2, a proline-rich domain between PDZ2 and PDZ3, and an acidic domain (dashed underline). The double underline within the GUK box indicates the original peptide obtained by amino acid sequencing. The ZO-3 sequence is available from the GenBank database under accession number AF023617.

Table II. Amino Acid Comparison of MAGUK Domains of ZO-1, ZO-2, ZO-3, dlg-A, and TamA

| Domain | ZO-1 | ZO-3 | ZO-2 | TamA | dlg-A |
|--------|------|------|------|------|------|
| PDZ1   | 57(72)| 55(74)| 59(80)| 46(66)| 42(66)|
| PDZ2   | 50(72)| 63(78)| 65(86)| 63(78)| 42(69)|
| PDZ3   | 63(81)| 48(69)| 70(86)| 48(69)| 42(69)|
| SH3    | 58(76)| 59(80)| 69(85)| 58(76)| 42(69)|
| GUK    | 52(69)| 52(71)| 67(82)| 46(68)| 34(53)|

Amino acid sequences in the indicated domains of human ZO-1 (44), canine ZO-3, ZO-2 (7), Drosophila dlg-A (46), and TamA (41), compared by the GCG GAP alignment program. Percent identity (percent similarity = percent identity + percent conserved substitutions).
2861–2841; Fig. 3; data not shown). Finally, aa sequence comparisons of all regions of ZO-1, ZO-2, and ZO-3 indicate the levels of similarity are generally highest in the MAGUK and acid domains, whereas most linker regions are less conserved (Table III). Such analysis also demonstrates that ZO-1 and ZO-2 are more closely related to each other in almost all regions than either is to ZO-3.

ZO-3 Localizes to the Tight Junction

Generation of antibodies against ZO-3 has been compromised by the homology between ZO-3, ZO-1, and ZO-2. Injection of fusion proteins corresponding to even the low similarity linker domains has produced antibodies that cross-react with ZO-1 and/or ZO-2 (see Fig. 9c). To circumvent these difficulties, a cDNA coding for full-length ZO-3 with a VSV-G cytoplasmic domain epitope tag at the COOH terminus was constructed. This construct was then transfected into MDCK cells to generate the stable MDCK/Z3 cell line. Immunoblot of a whole cell lysate from MDCK/Z3 cells with an anti–VSV-G antibody demonstrates the expression of an exogenous protein of ~130 kD (Fig. 6a, lane 1). No such band is detected in the parental, untransfected cell line (Fig. 6a, lane 2) or in a cell line stably transfected with vector alone (data not shown).

High stringency anti–VSV-G antibody immunoprecipitation from the MDCK/Z3 cell line likewise brings down a polypeptide that runs at approximately the same position as the original 130-kD band present in low-stringency ZO-1 immunoprecipitates (Fig. 6b, compare MDCK/Z3 lane 1 with lane LS). The slightly higher molecular mass of the exogenous protein in the MDCK/Z3 cells can be accounted for by the additional 1,338 D of the epitope tag.

Table III. Amino Acid Comparisons of ZO-1, ZO-2, and ZO-3

|          | ZO-3/ZO-1 | ZO-3/ZO-2 | ZO-1/ZO-2 |
|----------|-----------|-----------|-----------|
| Start    | 80(80)    | 89(89)    | 56(56)    |
| PDZ1     | 57(72)    | 61(76)    | 71(82)    |
| Link     | 25(54)    | 27(53)    | 29(53)    |
| PDZ2     | 50(72)    | 55(74)    | 65(86)    |
| Link     | 34(46)    | 29(48)    | 39(55)    |
| PDZ3     | 63(81)    | 59(75)    | 70(86)    |
| Link     | 53(82)    | 35(65)    | 53(76)    |
| SH3      | 58(76)    | 59(80)    | 69(85)    |
| Link     | 55(74)    | 53(76)    | 72(84)    |
| GUK      | 52(69)    | 52(71)    | 67(82)    |
| Link     | 26(42)    | 16(47)    | 47(58)    |
| Acid     | 43(60)    | 51(61)    | 60(71)    |
| Emd      | 17(41)    | 24(41)    | 25(43)    |

Amino acid sequences in the indicated domains of human ZO-1 (44) and canine ZO-3 and ZO-2 (7) compared by the GCG GAP alignment program. Percent identity (percent similarity = percent identity + percent conserved substitutions).
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plasm (14, 15). As shown in Fig. 9
domain of this protein believed to be oriented in the cyto-
ZO-3 and the COOH-terminal 148 aa of occludin, the
and ZO-3. We also assayed for direct interaction between
plex that includes ZO-1, ZO-2, and ZO-3, it does not test
though this result indicates the presence of a protein com-
binds both ZO-1 and ZO-2 from MDCK cell extracts. Al-
umoblotting with either anti–ZO-1 or ZO-2 antibodies.
with a high salt extract of MDCK cell membranes, washed,
length recombinant ZO-3 or a negative control peptide
able of interacting with other proteins from the tight
ZO-3 Directly Binds ZO-1 and Occludin, but Not ZO-2
We tested whether the ZO-3 cDNA codes for a protein ca-
other intercellular junctions, are free of label.
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counted for by the additional 1,338 D of the epitope tag.
No similar band is immunoprecipitated from the parental
cell line with anti–VSV-G (Fig. 6 b, MDCK/P lane I).
To determine where ZO-3 is localized in epithelial cells,
we immunofluorescently costained MDCK/Z3 monolayers
for the epitope-tagged ZO-3 and endogenous ZO-1, a
widely used marker of the tight junction in this cell type
(6, 38, 40). Fig. 7 shows that ZO-3 is localized to sites of
cell–cell interaction, identical to the distribution of ZO-1.
Additional staining of the cytoplasm is visible in the ZO-
3-stained cells (Fig. 7 a). It is not known if this is due to
exogenous overexpression or a novel distribution of the
protein.

ImmunoEM of an isolated MDCK/Z3 cell membrane
preparation was used to determine the ultrastructural
colocalization of ZO-3 and ZO-1. It was previously dem-
onstrated that ZO-1 is found exclusively at MDCK cell
tight junctions by immunoEM (38, 40). As shown in Fig. 8,
both ZO-1 and the ZO-3 are restricted to tight junctions in
these membranes, whereas all other membranes, including
other intercellular junctions, are free of label.

ZO-3 Directly Binds ZO-1 and Occludin, but Not ZO-2
We tested whether the ZO-3 cDNA codes for a protein ca-
pable of interacting with other proteins from the tight
junction in in vitro binding analyses. First, either full-
length recombinant ZO-3 or a negative control peptide
was bound to affinity beads. Resin was then incubated
with a high salt extract of MDCK cell membranes, washed,
and the bound proteins subjected to SDS-PAGE and im-
munoblotting with either anti–ZO-1 or ZO-2 antibodies.
As shown in Fig. 9 a, ZO-3, but not the control peptide,
binds both ZO-1 and ZO-2 from MDCK cell extracts. Al-
though this result indicates the presence of a protein com-
plex that includes ZO-1, ZO-2, and ZO-3, it does not test
for direct interactions among the proteins. Therefore, we
tested for direct binding using recombinant ZO-1, ZO-2,
and ZO-3. We also assayed for direct interaction between
ZO-3 and the COOH-terminal 148 aa of occludin, the
domain of this protein believed to be oriented in the cyto-
plasm (14, 15). As shown in Fig. 9 b, recombinant ZO-3
specifically binds in vitro transcribed/translated ZO-1. ZO-3
also binds directly to the cytoplasmic tail of occludin (Fig.
9 d). However, no binding was detected between recom-
binan ZO-3 and ZO-2 with our assay conditions (Fig. 9 e).

Discussion
Characterization of the tight junction is proceeding rapidly
and has stimulated advances in the fields of cell–cell inter-
actions and epithelial cell biology. In addition to the list
of proteins now found at the tight junction, we have learned
that two previously characterized tight junction compo-
nents, ZO-1 and ZO-2, are members of a larger protein
family that appear to function in the organization of spe-
cific areas of the cell surface (11, 21, 23, 24, 27, 41, 44).
Moreover, data suggest that some members of this family
are involved in signal transduction and/or tumor suppres-
sion (1, 41, 46, 47), highlighting the importance of analyz-
ing these molecules.

Here we present evidence of a novel member of the
MAGUK family of proteins found at the tight junction.
This 130-kD polypeptide, named ZO-3 because of homol-
gy to ZO-1 and ZO-2 (Figs. 5, Tables II and III) and loc-
alization at the tight junction (Figs. 7 and 8), contains 3
PDZ domains, an SH3 domain and a GUK region (Fig. 3).
The arrangement of these domains along the length of the
molecule is identical to that of ZO-1 and ZO-2, as well as
to the Drosophila proteins dlg-A and TamA. In common
with ZO-1 and ZO-2, but distinct from other MAGUK
members, ZO-3 contains an acidic domain at the COOH-
terminal end of the molecule. All three proteins (previ-
ously unnoted in ZO-1) also contain a basic region be-
tween PDZ1 and PDZ2. Although all three tight junction
molecules contain proline-rich regions, those in ZO-1 and
ZO-2 are located at the COOH-terminal ends of the mole-
cules whereas that in ZO-3 is found between PDZ2 and
PDZ3. Finally, using primers from the 3’ end of the ZO-3
cDNA, no evidence was obtained for an alternative splice
site in this region (data not shown). Alternative splice re-
regions in the COOH-terminal regions of ZO-1 and ZO-2
have been reported (7, 44).
ZO-3 was originally identified on the basis of coimmunoprecipitation with ZO-1 under specific conditions where some protein–protein interactions are preserved (reference 5; Fig. 1). We isolated and purified enough of this protein from MDCK cells for aa sequencing and subsequent cloning. This is similar to the approach used to identify ZO-2 (21), although our task was somewhat more difficult due to the smaller quantities of the 130-kD band that coprecipitated under these conditions (Fig. 1). It is unclear whether this reflects a smaller amount of ZO-3 present in cells or a reduced efficiency of coprecipitation. Despite the obvious identification of ZO-3 as another MAGUK element by sequence analysis, the continued characterization of the protein was complicated by our inability to generate anti-ZO-3 antisera that did not cross-react to ZO-1 and/or ZO-2 (Fig. 9 c). This problem extended through the injection of multiple fusion proteins corresponding to regions with lowest similarity to ZO-1 or ZO-2 into various antibody generating species. While our efforts to this end are ongoing, we constructed a full-length version of ZO-3 that contains an epitope tag at the COOH terminus. This version allowed us to determine that MDCK cells stably transfected with the construct express the exogenous protein at the predicted molecular mass by both immunoblot and immunoprecipitation (Fig. 6). Furthermore, this approach permitted us to localize ZO-3 using immunohistochemical techniques with an antiepitope antibody. Both immunofluorescence (Fig. 7) and immunoEM (Fig. 8) show that ZO-3 colocalizes with ZO-1 at the tight junction. To provide additional evidence that ZO-3 was a junctional protein, and to clarify binding interactions at the tight junction, we explored interactions between recombinant ZO-3 and tight junction proteins using in vitro affinity binding analyses (Fig. 9). Our results show that ZO-3 binds both ZO-1 and ZO-2 from MDCK cell extracts (Fig. 9 a), as predicted from the original coimmunoprecipitation observations. This indicates that our ZO-3 construct binds these proteins when they are present at low concentrations in a diverse protein mixture. However, these results do not address whether ZO-3 binds both proteins directly or through intermediary components. To that end, using purified recombinant proteins we determined that ZO-3 binds directly to ZO-1 but not to ZO-2. This indicates that the presence of ZO-2 in the coprecipitating ZO-1/ZO-2/ZO-3 complex from MDCK cell extracts is due to a direct interaction between ZO-2 and ZO-1 or another unidentified intermediary protein. However, the absence of binding between ZO-3 and ZO-2 should be interpreted with caution. It is possible that missfolding occurring during recombinant protein expression or the binding conditions themselves prevents detection of interaction. We also demonstrated that ZO-3 binds directly to the cytoplasmic 148-aa tail of occludin. Our results, combined with previous studies, indicate that occludin interacts directly with both ZO-1 (15) and ZO-3 (Fig. 9 d). ZO-2 is likely bound to this complex via ZO-1 (5, 16, 21; Fig. 1). ZO-1 also directly interacts with AF-6 (47). It has not been determined...
if ZO-2 binds directly to occludin or if AF-6 interacts with any other junctional component.

Limited information is available on the function of any of the tight junction proteins. Data clearly indicate that occludin has a role in the paracellular permeability barrier (6, 31, 45), as expected from a transmembrane element localized to the fibrils visible in freeze-fractured tight junctions (13). Evidence also suggests that additional transmembrane components may be present at the tight junction (6). The function of the cluster of peripheral membrane proteins found at the tight junction is less evident. The presence of actin filaments at the tight junction (29) indicates that some of these proteins may be involved in linking transmembrane elements to the cytoskeleton, and evidence suggesting that ZO-1 may function in this regard has recently been published (19). However, it is the MAGUK protein family members found at the tight junction, now totaling three with the data presented in this paper, that are the focus of much current investigation.

The founding member of the MAGUK family is the lethal(1)discs-large-1 (dlg) tumor suppressor gene product (dlg-A) of Drosophila, and information has been derived from genetic analysis of this gene. Mutations in the GUK domain of Drosophila dlg-A result in loss of normal epithelial cell polarity and neoplastic overgrowth in the larval imaginal disc, suggesting that this domain is important for normal protein function and that the protein plays a role in tumor suppression (46). Mutations in the PDZ, SH3, or GUK domains of dlg also disrupt normal synaptic structure at the neuromuscular junction (28), consistent with evidence that the PDZ domains bind synaptic ion channels (23, 27). Binding interactions have also been defined for the SH3 (4) and GUK domains (24), as well as other regions (19) of MAGUK proteins. Taken as a whole, the presence of multiple domains capable of specific protein–protein interactions suggests that MAGUK proteins at the tight junction act as connector molecules on the cytoplasmic surface of the plasma membrane.

In addition to the MAGUK domains, ZO-1, ZO-2, and ZO-3 have other common and distinguishing features (Fig. 10). The presence of three homologous proteins at the tight junction raises several questions. Do these proteins have unique functions or is their homology indicative of functional redundancy related to an overall critical role? If there are unique aspects to the function of these proteins, it is likely to fall within the regions linking the MAGUK domains or the COOH-terminal tails where aa similarity between them is the lowest (Table III). Will these molecules, if structurally altered or ablated, result in the neoplastic transformation observed for dlg-A? Genetic analysis in mammalian systems, although more difficult than in Drosophila, will clearly be instructive. What protein domains are responsible for the specific binding interactions among tight junction proteins? Investigations in this regard are ongoing in several laboratories, with obvious focus on the PDZ domains of the tight junction MAGUK subfamily. Finally, what roles might these proteins play in normal tight junction gate and fence physiology? There is now evidence linking paracellular permeability to tyrosine phosphorylation of ZO-1 (36), but otherwise there is no direct information on the function of ZO-1, ZO-2, or ZO-3. Although the molecular composition of the tight junction is now becoming understood, the understanding of tight junction molecular biology is still in its infancy.

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