

Localization of a Symbiosis-Related Protein, Sym32, in the *Anthopleura elegantissima*–*Symbiodinium muscatinei* Association

J. A. SCHWARZ* AND V. M. WEIS

Department of Zoology, 3029 Cordley Hall, Oregon State University, Corvallis, Oregon 97331

Abstract. Cnidarian–dinoflagellate symbioses are widespread in the marine environment. Growing concern over the health of coral reef ecosystems has revealed a fundamental lack of knowledge of how cnidarian–algal associations are regulated at the cellular and molecular level. We are interested in identifying genes that mediate interactions between the partners, and we are using the temperate sea anemone *Anthopleura elegantissima* as a model. We previously described a host gene, *sym32*, encoding a fasciclin domain protein, that is differentially expressed in symbiotic and aposymbiotic *A. elegantissima*. Here, we describe the subcellular localization of the *sym32* protein. In aposymbiotic (symbiont-free) hosts, *sym32* was located in vesicles that occur along the apical edges of gastrodermal cells. In symbiotic hosts, such vesicles were absent, but *sym32* was present within the symbiosome membranes. Sym32 (or a cross-reactive protein) was also present in the accumulation bodies of the symbionts. Although the anti-*sym32* antiserum was not sufficiently specific to detect the target protein in cultured *Symbiodinium bermudense* cells, Western blots of proteins from two *Symbiodinium* species revealed a protein doublet of 45 and 48 kDa, suggesting that the symbionts may also produce a fasciclin domain protein. We suggest that host *sym32* is relocated from gastrodermal vesicles to the symbiosome membrane when symbionts are taken into host cells by phagocytosis.

Introduction

Intracellular associations between eukaryotic microorganisms and animal hosts encompass a wide range of interactions ranging from parasitic to mutualistic. Most eukaryotic microbes that infect animals reside within a membrane-bound vacuole within the cytoplasm of host cells (Hackstadt, 2000). The formation of the vacuole is a dynamic process that is initiated either by active invasion of the host cell by the microbe—for example, the parasite *Toxoplasma* (Dobrowolski and Sibley, 1996)—or by phagocytic uptake of the microbe by the host cell—for example, the parasite *Leishmania* (Courret *et al.*, 2002) and the symbiont *Symbiodinium* (Fitt and Trench, 1983).

Studies on eukaryotic microbial parasites show that, in the vast majority of cases, the nascent vacuole that contains the microbe fails to continue through the complete endocytic pathway that culminates in acidification of the vacuole and fusion with lysosomes. Instead, the microbial inhabitant actively interferes with one or more steps in the normal process of fusion between the vacuole and endocytic organelles that direct the vacuole through the phagocytic process (Mellman, 1996). The result is that the microbe successfully transforms what would have been a phagolysosome into a compartment that is hospitable for growth, replication, or differentiation into various life-history stages (Hackstadt, 2000; and for examples, see Mukkada *et al.*, 1985; Sinai and Joiner, 1997).

In the marine environment, associations between animals and eukaryotic microbes include mutualistic as well as parasitic interactions. One prevalent mutualistic association occurs between cnidarians (most commonly sea anemones and corals) and photosynthetic dinoflagellates (usually *Symbiodinium* spp.). These associations are characterized by reciprocal nutritional interactions between host and

Received 14 April 2003; accepted 27 August 2003.

* To whom correspondence should be addressed. Current address: Department of Microbiology and Immunology, D305 Fairchild Building, 299 Campus Drive, Stanford University, Stanford, CA 94305. E-mail: jschwarz@stanford.edu

symbiont (Falkowski *et al.*, 1984; Muller-Parker and D'Elia, 1998). The photosynthetic symbionts contribute glycerol and other organic compounds to host metabolism (Lewis and Smith, 1971; Battey and Patton, 1987; Muscatine, 1990), and the host contributes nitrogen (Wang and Douglas, 1998, 1999) and carbon dioxide (Weis, 1993) for algal photosynthesis. These associations occur in the photic zones of both temperate and tropical benthic habitats, and they thrive in nutrient-poor tropical marine environments because they conserve and recycle nutrients.

In its associations with dinoflagellates, the host cnidarian most commonly houses symbionts within gastrodermal cells, in a vacuole of phagosomal origin. The initial infection, during which the dinoflagellate symbionts are internalized, typically occurs when dinoflagellates that enter the host's mouth are taken into phagocytic gastrodermal cells that line the gastric cavity (Colley and Trench, 1983; Fitt and Trench, 1983; Schwarz *et al.*, 1999, 2002). The phagosome, through unknown mechanisms, fails to fuse with lysosomes (Fitt and Trench, 1983), and the dinoflagellates remain undigested within the vacuole. Ultimately, the dinoflagellates reside within a compartment delineated by multiple membranes (Taylor, 1968, 1987; Wakefield *et al.*, 2000). Historically, the origin of the multiple membranes that surround the symbiont has been uncertain. Recently, immunolocalization studies using host-specific and dinoflagellate-specific monoclonal antibodies suggest that only the outermost membrane originates from the host, and all of the inner membranes originate from the dinoflagellates, perhaps accumulating from repeated cycles of ecdysis within the host vacuole (Wakefield and Kempf, 2001).

We have been interested in identifying host genes that play roles in symbiotic interactions in cnidarian–dinoflagellate symbioses (Weis and Levine, 1996; Weis and Reynolds, 1999; Reynolds *et al.*, 2000). We have used as a model system the temperate symbiotic sea anemone *Anthopleura elegantissima* (Brandt, 1835), which is abundant in the intertidal region of the eastern Pacific, from Mexico through Alaska. This species is able to form associations with two species of dinoflagellates, *Symbiodinium californium* and *S. muscatinei*. The presence of one or more of the symbionts within a particular host depends upon microhabitat differences that are created along temperature and light gradients that occur along latitudinal and intertidal ranges. Along the Oregon coast, most hosts contain only a single symbiont, *S. muscatinei* (LaJeunesse and Trench, 2000).

Using biochemical and molecular approaches, we have identified a number of host genes that are likely to function in mediating host-symbiont interactions (Reynolds *et al.*, 2000; Weis and Levine, 1996; Weis and Reynolds, 1999). One of these, *sym32*, encodes a protein that belongs to a class of cell adhesion proteins called fasciclin domain proteins (Reynolds *et al.*, 2000). Fasciclin domain proteins share low overall sequence identity, but all possess between

one and four repeats of three highly conserved “fasciclin” domains that are believed to function as adhesive domains in cell–cell and cell–extracellular matrix interactions (Hu *et al.*, 1998). Members of this family have been identified in organisms as diverse as mycobacteria (Harboe and Nagai, 1984; Harboe *et al.*, 1995; Terasaka *et al.*, 1989), *Volvox* (Huber and Sumper, 1994), insects (Zinn *et al.*, 1988), sea urchins (Brennan and Robinson, 1994), and humans (Skonier *et al.*, 1992; Takeshita *et al.*, 1993).

To further investigate the role played by *sym32* in symbiotic interactions between cnidarian hosts and dinoflagellate symbionts, we used immunocytochemical techniques to examine the distribution of the *sym32* protein within the *A. elegantissima*–*S. muscatinei* association. In this paper we demonstrate that *sym32* protein is differentially distributed in symbiotic and aposymbiotic *A. elegantissima* both at the cellular and subcellular level. Of particular interest, *sym32* antiserum labels the multiple layers of membrane that surround the symbiont within the host cell. We also show that anti-*sym32* antiserum specifically labels the accumulation body of dinoflagellates residing within host gastroderm. Western blots of proteins from two *Symbiodinium* species revealed a protein doublet of 45 and 48 kDa (45/48 kDa) that cross reacts with the *sym32* antiserum; but in immunolocalization studies, the antiserum was insufficiently specific to detect the target protein in cultured specimens of *S. bermudense*. Possibly, both the host and symbiont produce fasciclin domain proteins that interact *via* the fasciclin adhesive domain.

Materials and Methods

Animal maintenance

Symbiotic and aposymbiotic specimens of *A. elegantissima* were collected at low tide from the intertidal zone at Seal Rock, Oregon. Aposymbiotic anemones were taken from under rock overhangs or crevices where there was little or no light to support the growth of symbiotic dinoflagellates. Symbiotic anemones were taken from the open rock benches that are exposed to light. Anemones were transported to the laboratory, where they were maintained in an 11 °C recirculating seawater aquarium on a 12:12 h light:dark cycle. Anemones were fed previously frozen adult brine shrimp about once a week.

Light-level immunocytochemistry

Anemones. Tentacles from both symbiotic and aposymbiotic specimens of *A. elegantissima* were clipped and immediately transferred to tissue freezing medium (Triangle Biomedical Sciences) and frozen at –80 °C. Tentacles were cryosectioned at –20 °C on a Reichert-Jung cryostat (20- μ m sections) and placed on polylysine slides, then immersed in 4% paraformaldehyde fixative in phosphate

buffered saline (PBS: 10 mM phosphate buffer, pH 7.2, + 150 mM NaCl) for 1.5 h. Sections on slides were rinsed three times, 5 min each time, in PBS with 0.5% BSA; dehydrated in a methanol series (25%, 50%, 75%, 100%, 75%, 50%, 25%); and rinsed again in PBS/BSA. Sections were incubated in a blocking solution of 1:200 dilution of goat serum:PBS/BSA for 30 min at room temperature and then rinsed three times, 5 min each time, in PBS/BSA. Slides were incubated for 1 h in either a 1:2000 dilution of sym32 antiserum from rabbit (antibody development described in Reynolds *et al.*, 2000) in PBS/BSA or in a 1:2000 dilution of preimmune serum from the same rabbit. Sections were rinsed three times, 5 min each time, in PBS/BSA and then incubated for 1 h in a 1:200 dilution of goat anti-rabbit IgG–5-nm colloidal gold conjugate (Ted Pella). Slides were rinsed as above. Gold particle labeling was silver-enhanced using a silver enhancement kit (Ted Pella). To stop color development, slides were washed in ePure water. Coverslips were affixed with a glycerol mount and sealed with finger-nail polish.

Cultured Symbiodinium bermudense cells. Immunofluorescence was used to investigate whether the symbiont-produced 45/48 kDa cross-reactive protein (identified from Western blots, described below) could be localized to symbionts free from host cells. Cells of *S. bermudense* (CCMP830) were grown in sterile filtered seawater enriched with f/2-Si media at about 100 μ E light on a cycle of 12 h light to 12 h dark at 25 °C. Cells were collected by centrifugation from liquid media and resuspended into 3% paraformaldehyde in PBS. After fixation for 30 min, cells were given two 10-min washes in PBS and transferred to PBS. Cells were incubated 30 min in blocking solution (PBS + 3% BSA); 30 min in PBS/BSA/0.2% Triton X-100; 1 h in preimmune serum or anti-sym32 antiserum diluted with PBS/BSA/Triton X to 1:50, 1:200, 1:2000; 5 min in PBS, repeated five times; 1 h in 1:200 Alexa Fluor 488 goat anti-rabbit IgG in PBS/BSA; and 5 min in PBS, repeated five times. After incubation, the cells were viewed under an Olympus BX-60 fluorescence microscope.

EM-level immunocytochemistry

Anemones. Immunocytochemistry was performed on three occasions using symbiotic anemones collected at different times and on one aposymbiotic anemone. Tentacles from aposymbiotic and symbiotic anemones were clipped and immersed in 1% paraformaldehyde, 1% glutaraldehyde fixative in PBS for 1.5 h. Tentacles were rinsed three times, 10 min each time, in PBS and then dehydrated for 15 min in each concentration of a methanol (MeOH) series (15%, 30%, 50%, 85%, 95%, 100%, 100%). Tentacles were infiltrated with LR White resin on a rotating table in a series of MeOH dilutions (1:3 LR White:MeOH overnight, 1:1 overnight, 100% LR White for 3 h), and then placed in gelatin

capsules in fresh LR White. LR White was allowed to polymerize at 52 °C for 2 days.

Ultra-thin, gold–silver sections were cut with a diamond knife and placed onto Formvar-coated nickel grids. These grids were processed for immunocytochemistry as follows: they were immersed in blocking solution (PBS + 5% BSA) for 15 min, incubated in a 1:1000 dilution of sym32 antiserum or a 1:1000 dilution of preimmune serum in PBS for 1.5 h, rinsed 3 times, 10 min each time, in PBS/BSA + 0.1% Tween 20, incubated in a 1:75 dilution of EM grade goat anti-rabbit IgG–15-nm colloidal gold (Ted Pella) in PBS for 1 h, rinsed as above, rinsed in ePure water for 5 min, and then allowed to dry. Grids were stained in 2% uranyl acetate for 5 min, rinsed by dipping in water 10 times each in three changes of water, then immediately stained in 0.4% lead acetate for 3 min, with water rinses as above, and then air dried. Between 5 and 10 grids of each type of anemone were viewed under 60 kV using a CM-12 Phillips transmission electron microscope.

Cultured Symbiodinium bermudense cells. Cells were collected as described in the light microscopy section, fixed as described for anemone tentacles, and processed essentially as described for anemone tentacles. Several dilutions of anti-sym32 antiserum and preimmune serum were tested (1:10, 1:50, 1:200, 1:500, 1:1000, 1:2000), as well as various dilutions of either Tween-20 or Triton X (0%, 0.1%, 1%) in the following solutions: blocking solution, primary antibody solution, wash solution.

Preparation of anemone and dinoflagellate proteins: one- and two-dimensional SDS-PAGE and Western analysis

Proteins were isolated from the host as follows: a host anemone was removed from an 11 °C recirculating aquarium and flash-frozen in liquid nitrogen. The anemone was minced with a razor blade, and placed into a glass grinder with a Teflon pestle driven by a hand drill in four volumes ice-cold grinding buffer (100 mM Tris, 100 mM NaCl, 10 mM EDTA) with protease inhibitors (Sigma: 5 μ l per 10 ml buffer). The homogenate was placed into a centrifuge tube and the grinder was rinsed with two volumes of buffer (v:w anemone tissue), which was added to the tube and mixed well. The remaining homogenate was centrifuged at 16,000 $\times$ g for 10 min at 4 °C to remove algal cells and host cell debris and membranes from the homogenized anemone tissue. The supernatant was removed to a new tube and centrifuged again. Protein concentration was determined on this cleared homogenate using the Bradford assay (Pierce Coomassie reagent). Host proteins prepared according to this protocol are free from contamination by symbiont proteins (Weis and Levine, 1996).

Proteins were isolated from symbionts that had been either continuously maintained in culture with no host contact for many generations or freshly isolated from an

A. elegantissima host. Many species of *Symbiodinium* can be isolated from their hosts and brought into culture in nutrient-supplemented seawater. These symbionts are therefore free from any host cell contact. We obtained frozen pelleted symbionts from cultures of *S. bermudense*, which was originally isolated from the tropical sea anemone *Aiptasia pallida*. A chunk of the pelleted symbionts (about 100 μ l in volume) was briefly ground in a glass tissue grinder with a Teflon pestle in an equal volume of grinding buffer with protease inhibitor cocktail. Examination under a light microscope revealed that nearly all symbionts were still intact after this step. An equal volume of acid-rinsed glass beads (Sigma; 425–600 μ m) was added and the mixture alternately vortexed for 15–30 s and placed on ice for about 30 s, for a total of 20 times. With repeated vortexing, the homogenate became intensely orange, likely indicating the release of the major water-soluble accessory pigment, peridinin-chlorophyll protein. By this means, at least 75% of symbionts were broken open, as determined by light microscopy. With a syringe and a 24-gauge needle, the homogenate was removed from the glass beads and centrifuged at $16,000 \times g$ for 10 min at 4 °C to remove cellular debris. The supernatant was placed into a new tube and again centrifuged. This cleared supernatant fraction was then assayed for protein concentration, as described above, and then prepared for one-dimensional or two-dimensional SDS-PAGE, as described below.

Proteins from freshly isolated symbionts were prepared by isolating symbionts from a host and then extracting proteins using glass beads to fracture the symbiont cell wall and release the contents of the cytoplasm. A host anemone weighing about 2 g was removed from an 11 °C recirculating aquarium and flash-frozen in liquid nitrogen. The anemone was minced with a razor blade and placed into a glass grinder with 3 ml of grinding buffer plus protease inhibitor. All subsequent steps were performed on ice. The anemone was ground with a Teflon pestle instead of a ground glass pestle to homogenize the animal tissues without shearing the cell walls of the symbionts. This homogenate was centrifuged at $2000 \times g$ for 10 min to pellet the symbionts. The pellet, about 300 μ l in volume, was partially cleaned of anemone debris by regrinding the pellet in grinding buffer using a glass tissue grinder with a Teflon pestle (this regrinding step was sufficient to break up the pellet, but not break open the symbionts) and reconcentrating the symbionts by centrifugation. The partially cleaned pellet was ground a final time before adding 500 μ l of buffer with protease inhibitor cocktail and an equal volume of prerinsed glass beads. This resuspended pellet contained a significant amount of host tissue, as revealed by the presence of numerous nematocysts. We then followed the same vortexing and centrifugation protocol as described above. The cleared supernatant fraction (intensely orange in color) was used for one-dimensional SDS-PAGE, as described below.

One-dimensional SDS-PAGE with 10% Nu-PAGE Bis-Tris gels (Invitrogen) was performed on proteins from host tissue and from freshly isolated, and cultured symbiont proteins. Samples were denatured and prepared for electrophoresis using LDS buffer + DTT (Invitrogen) according to manufacturer's instructions; 10 μ g of protein was loaded for each sample. Electrophoresis was performed in MOPS buffer according to the manufacturer's instructions. Gels were transferred to 12.5 mM Tris, 100 mM glycine, 10% MeOH for 20 min, and proteins were electrophoretically transferred onto nitrocellulose membrane for 1.25 h at 100 V in a BioRad chamber.

Two-dimensional SDS-PAGE was performed using proteins extracted from freshly isolated symbionts. Proteins were extracted as described above, except that no NaCl was used in the buffer, as salt interferes with isoelectric focusing. The SDS-PAGE was carried out on a Multiphor II system (Amersham Pharmacia), according to the manufacturer's instructions and as described in Reynolds *et al.* (2000). Thirty microliters of symbiont homogenate containing 60 μ g of protein was used for isoelectric focusing on an 180-mm IPG strip, pH 3–10. After isoelectric focusing, the IPG strip was equilibrated and placed on a 12% ExcelGel; electrophoresis was performed according to manufacturer's instructions. After electrophoresis, the gel was placed into transfer buffer (50 mM Tris, 40 mM glycine, 0.04% SDS, 20% methanol) for 20 min. The gel was removed from the plastic backing, and proteins were transferred to a nitrocellulose membrane under a discontinuous buffer system (Multiphor II system from Amersham).

For Western analysis, the membranes from one- and two-dimensional SDS-PAGE were incubated at 4 °C overnight in blocking buffer (TBS: 20 mM Tris, 500 mM NaCl, Ph 7.5, + 5% powdered milk + 0.1% Tween-20). The following morning, the membrane was washed for 15 min in TBS + 0.5% Tween-20 (TBST); incubated for 45 min in a 1:1500 dilution of anti-sym32 antiserum: block buffer; rinsed 10 min each in TBS, TBST, TBS; incubated 45 min in a 1:5000 dilution of HRP-antirabbit IgG (Amersham Pharmacia); and washed as before. Sym32 protein was detected by chemiluminescence using ECL detection reagents (Amersham Pharmacia) and exposing membranes to film for 1 min.

Results

Microscopy of anemone tentacles

Cryosectioned tentacles. Cryosectioned tentacles of aposymbiotic and symbiotic anemones were incubated with (1) preimmune serum as a negative control for endogenous staining or (2) sym32 antiserum. Staining for sym32 in aposymbiotic tentacles was distinct from that in symbiotic tentacles, relative to preimmune controls (Fig. 1). In both symbiotic and aposymbiotic tentacles, preimmune controls

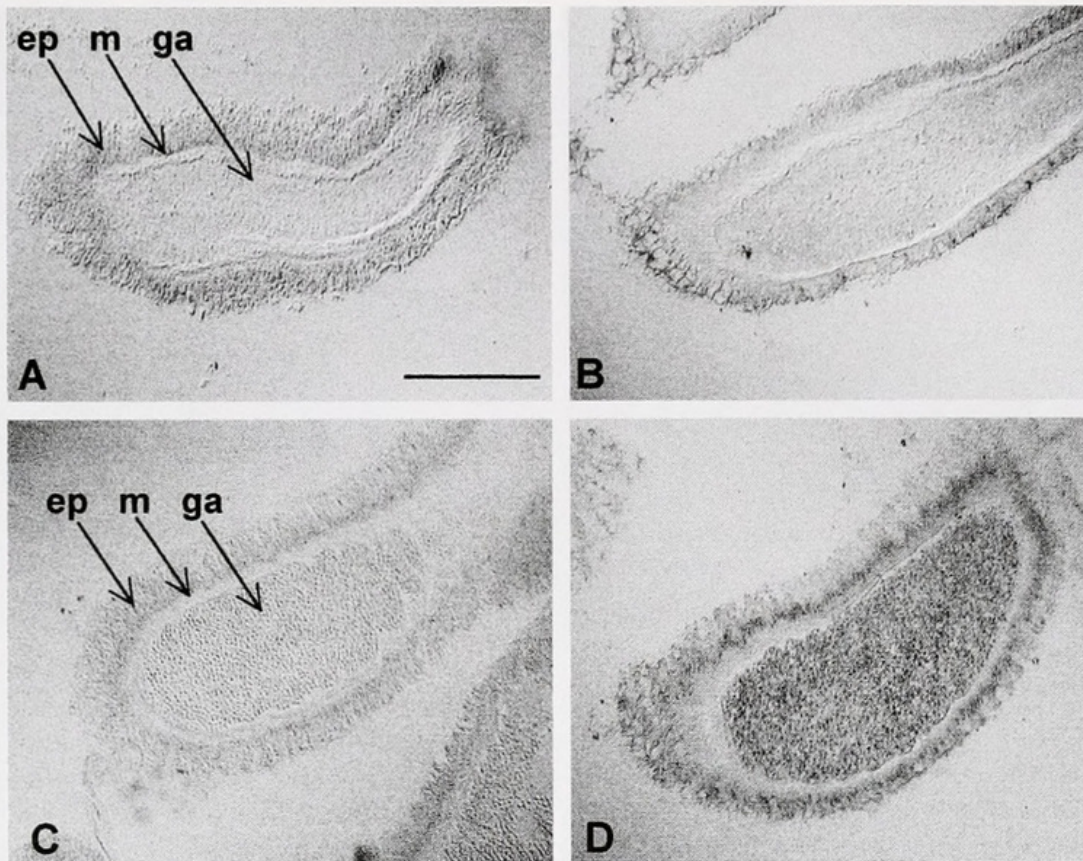


Figure 1. Light micrographs showing immunolocalization of sym32 protein within cryosections of tentacles from aposymbiotic (A and B) and symbiotic (C and D) *Anthopleura elegantissima*. The spherical symbionts can be clearly seen within the gastrodermis of symbiotic tentacles. Sections were incubated in either preimmune serum (A and C) or sym32 anti-serum (B and D), and sym32 was visualized using silver enhancement of colloidal gold labeling. Sym32 levels are high in the gastrodermis of symbiotic anemones, low in the gastrodermis of aposymbiotic anemones, faint in the epidermis of both types of anemones, and absent in the mesoglea of both types of anemones. Host tissue layers are marked as ep = epidermis, ga = gastrodermis, m = mesoglea. Scale bar = 0.3 mm for all panels.

showed light brown staining in epidermal and gastrodermal tissues, and no staining in the mesoglea. In aposymbiotic tentacles incubated in sym32 antiserum, staining in the epidermal and gastrodermal layers was slightly darker than in the preimmune controls. In symbiotic tentacles, staining in the epidermis was also slightly darker than in the preimmune controls, and in the gastrodermis, where dinoflagellates are housed, it was significantly darker. The mesogleal layer of both aposymbiotic and symbiotic tentacles remained unstained.

Electron microscopy. To further examine the location of sym32 within the host–symbiont association, we performed EM-level colloidal gold immunocytochemistry using sym32 antiserum to label the sym32 protein within thin sections of resin-embedded tentacles from one aposymbiotic and three symbiotic anemones (Figs. 2–4). We examined between 15 and 25 sections from each anemone. We also performed negative controls with preimmune serum to check for non-specific labeling of the tissues. In all cases, the preimmune controls were almost completely free of gold-sphere labeling (data not shown).

In aposymbiotic tentacles, sym32 gold-sphere labeling was associated exclusively with medium-density vesicles located within both epidermal and gastrodermal cells (Fig. 2). There was no evidence of any sym32 label within the mesogleal layer, and the pattern of distribution of the sym32-containing vesicles in the epidermal cells was distinct from that in the gastrodermis. The vesicles were relatively uncommon in the epidermis (Fig. 2A, B) but more abundant in the gastrodermis, where they were concentrated along the apical end of the gastroderm, near the interface between the gastroderm and the gastric cavity (Fig. 2C, D).

In symbiotic tentacles, the pattern of distribution in the epidermis was the same as in aposymbiotic tentacles; sym32 gold-sphere labeling was contained within vesicles that were relatively sparsely distributed, most commonly occurring near nematocysts. In contrast, the distribution of sym32 within the gastrodermis was dramatically different. The sym32-containing vesicles that were so abundant in aposymbiotic gastroderm were not present in symbiotic gastroderm. Instead, the sym32

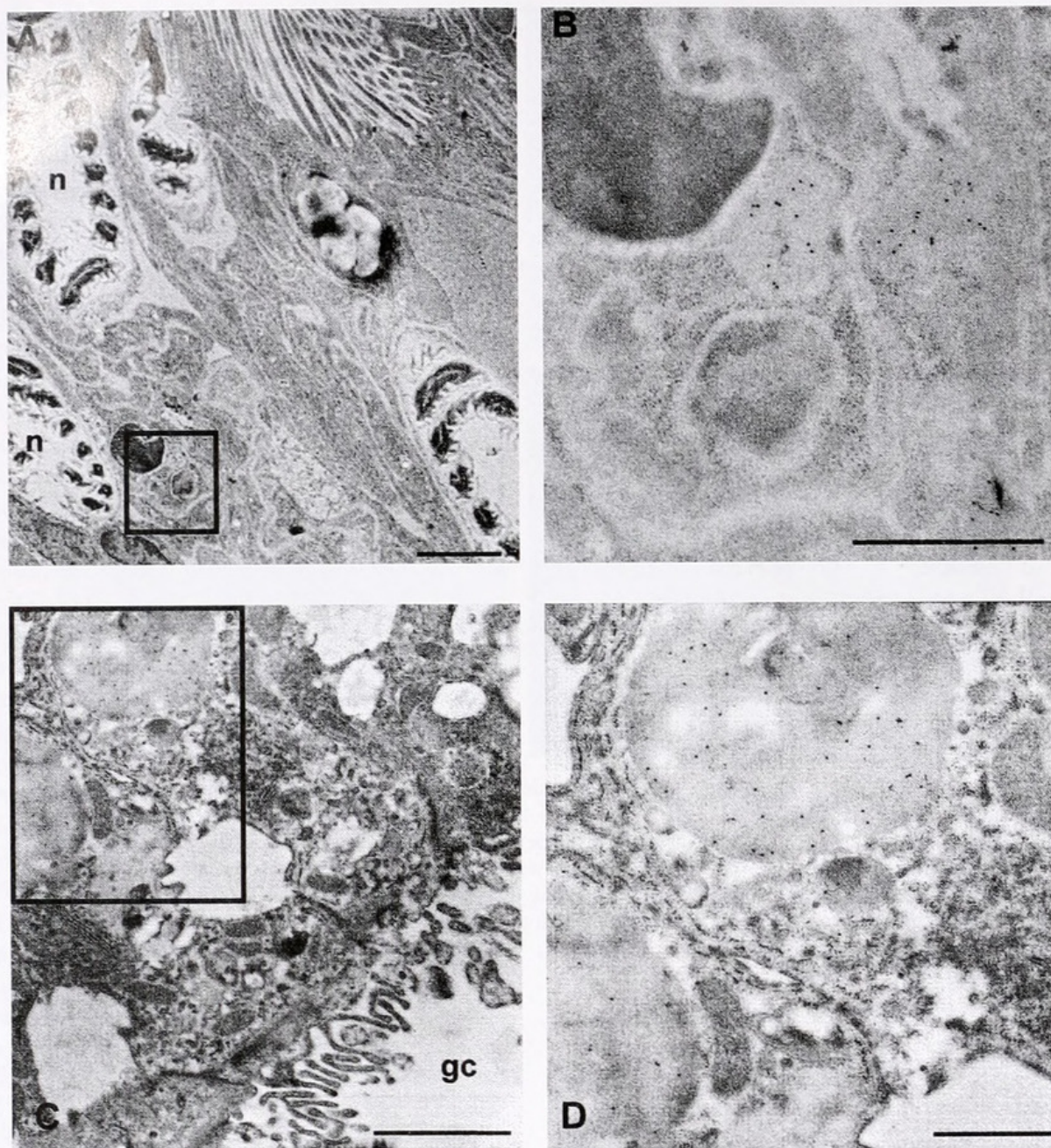


Figure 2. Transmission electron micrographs of immunogold-labeled sections from tentacles of aposymbiotic anemones. Gold spheres, visible as black dots, indicate the presence of sym32. (A) Epidermal cells with nematocysts (n). (B) Enlargement of the boxed section of A, with gold spheres labeling vesicles located near nematocysts. (C) Gastrodermal cells adjacent to the gastric cavity (gc). (D) Enlargement of the boxed section of C, showing gold spheres within vesicles in the gastrodermal cells. Scale bars = 2 μm (A, C) and 1 μm (B, D).

label was associated with the multiple membranes that enclose the dinoflagellate symbiont within the host cell (Fig. 3A, B). Gold spheres were diffusely arranged within these membranes, not clearly associated with any single membrane layer. To confirm that this labeling was specific to the membranous layers, we quantified the staining relative to areas outside the membranes. The membranous layers contained an average of 12.2 ± 4.65 (SD), $n = 19$, while equivalent areas outside the membranous layers contained an average of 1.0 ± 1.1 , $n = 19$.

Symbiodinium within host cells. In addition to the sym32 labeling within the membranes that surround the symbionts, there was a significant amount of labeling within the symbionts themselves (Fig. 4). Specifically, gold spheres were located within the accumulation body, a poorly described organelle that is believed to function in the endocytic pathways of dinoflagellates. The density of labeling within the accumulation bodies was highly variable: some contained only a few gold spheres, while others contained hundreds (average = 56.4 ± 83.2 [SD] gold spheres/ μm^2 , $n = 18$).

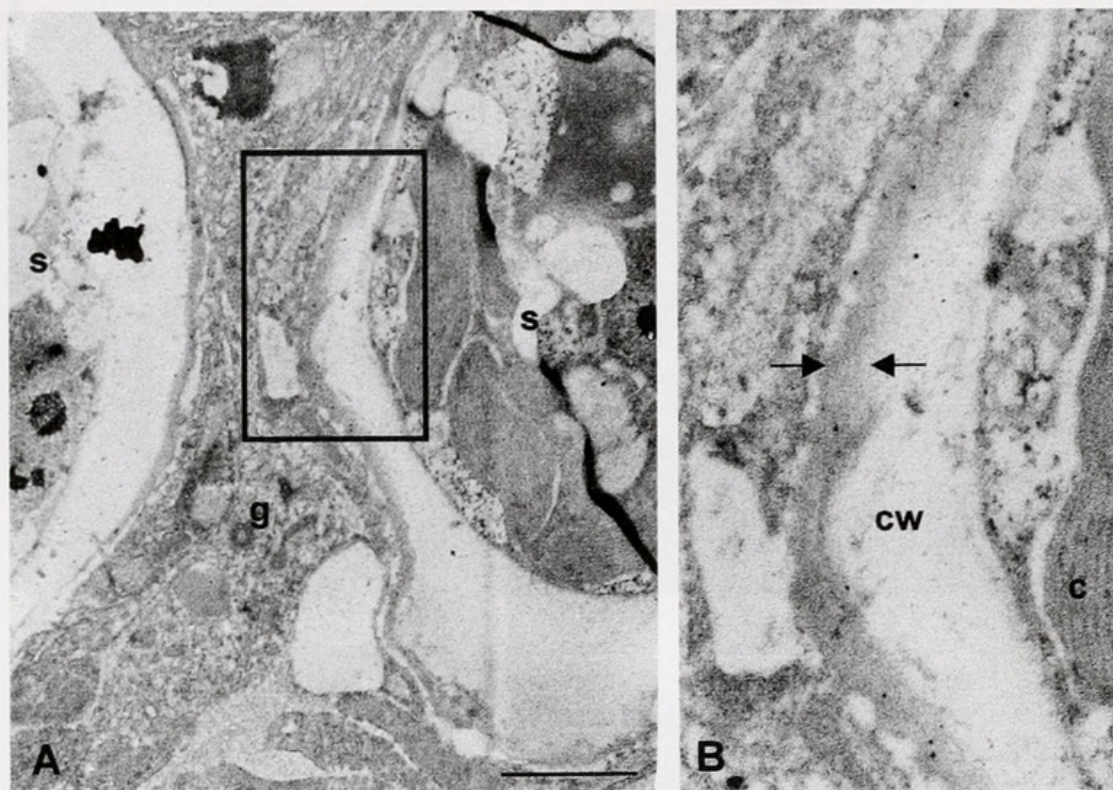


Figure 3. Transmission electron micrographs of immunogold-labeled sections of tentacles from symbiotic *Anthopleura elegantissima*. (A) Illustrates the presence of dinoflagellates within host gastrodermal cells. (B) Enlargement of boxed area in A, showing gold spheres associated with the multiple layers of membrane that surround the dinoflagellate. The arrows delineate the margins of the multiple membranes surrounding the dinoflagellate. Preimmune controls showed virtually no gold-sphere labeling (not shown). c = symbiont chloroplast, cw = symbiont cell wall, g = gastrodermal cell of the host, s = dinoflagellate symbiont. Scale bar = 2 μ m.

Western blots

The presence of gold-sphere label within the accumulation bodies of the symbionts suggested that the symbionts were producing a sym32 homolog. We performed Western analysis using anti-sym32 antiserum to look for cross-reactive proteins in homogenates from symbionts freshly removed from a host anemone and from cultured symbionts that were not in contact with host cells. Anti-sym32 Western blots of one-dimensional gels from homogenates of freshly isolated *Symbiodinium muscatinei* revealed three bands (Fig. 5A, lane 2). The 32-kDa band, identical in size to a band in host-only homogenate (lane 1), is probably due to contamination from host sym32. This was expected, as protein preparations of the symbionts are invariably contaminated by host proteins (Weis *et al.*, 1998). A 48-kDa band and a faint 45-kDa band below it suggest the presence of cross-reactive proteins that are produced by the symbionts. Homogenates of cultured algae (*Symbiodinium bermudense*) that were never in contact with host tissues (lane 3) also contained the same 45/48-kDa doublet but lacked the 32-kDa host band. Western blots of two-dimensional gels of freshly isolated *S. muscatinei* homogenates revealed two spots

with distinctly different molecular weights and isoelectric points (pI) (Fig. 5B). A cross-reactive spot at 32 kDa, 8.2 pI, corresponds exactly with host sym32 (Reynolds *et al.*, 2000), and again is probably due to host contamination. In addition there was a 48-kDa spot with a pI range of 4.3 to 4.5. The 45/48-kDa protein doublet that is present in cultured *S. bermudense* and in *S. muscatinei* freshly harvested from a host, and is also faintly visible in the host lane, therefore represents a protein produced by *Symbiodinium* both when it is in symbiosis with a host, and when it is free-living.

Microscopy of cultured *Symbiodinium bermudense* cells

We were interested in determining the location of the symbiont-produced 45/48-kDa protein doublet. We therefore used the anti-sym32 antiserum (which was developed against recombinant host sym32 protein), to localize the target protein in cultured specimens of *S. bermudense*. We used two immunolocalization methods. For intact cells, we used immunofluorescence, in which a fluorescent secondary antibody is detected by fluorescence microscopy. For sectioned cells, immunoelectron microscopy allowed us to detect any patterns in staining

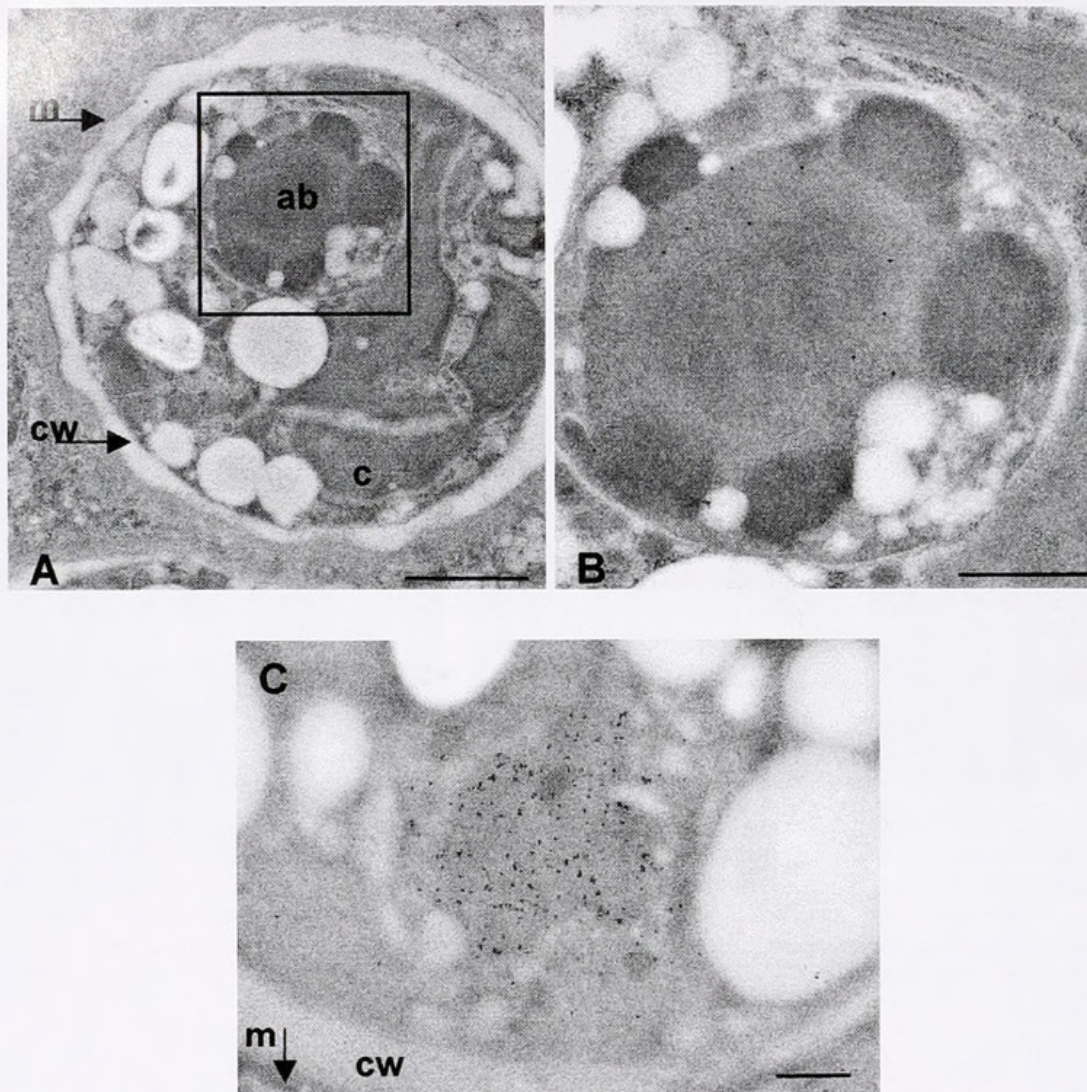


Figure 4. Transmission electron micrographs of immunogold-labeled sections of dinoflagellate symbionts contained within host gastrodermal cells. (A) Dinoflagellate contained within a host gastrodermal cell. (B) Enlargement of the accumulation body, shown boxed in A, illustrating sparse gold labeling of the dinoflagellate accumulation body. (C) Region around the accumulation body of another symbiont (section not counterstained) showing intense labeling specific to the accumulation body. The cell wall (cw) and membrane layers (m) are visible as concentric gray rings around the symbiont. Sections incubated with preimmune serum showed virtually no gold-sphere labeling (data not shown). m = membranes surrounding the dinoflagellate, cw = dinoflagellate cell wall, c = dinoflagellate chloroplast, ab = accumulation body of the dinoflagellate. Scale bar = 2.5 μ m (A), 1.0 μ m (B, C).

at the subcellular level. Despite testing many concentrations of antiserum and buffer solutions, we were unable to detect a pattern of staining of the target protein in cultured cells of *S. bermudense*. With the immunofluorescence method, preimmune controls looked identical to antiserum-incubated specimens at all dilutions of serum that we tested. With immunoelectron microscopy, we could detect no specific staining to any particular compartment within the cell, even though the background staining varied from almost no gold-sphere labeling at the 1:2000 dilutions to heavy labeling at the 1:10 dilutions. In the preimmune controls, labeling was restricted to a few, widely scattered spheres.

Discussion

The sym32 protein is distributed among different subcellular compartments in symbiotic and aposymbiotic anemones. Most notably, the sym32-containing vesicles that are so abundant in the gastroderm of aposymbiotic hosts are absent from symbiotic hosts; instead, sym32 localizes to the symbiosome membranes. This suggests that the internalization of symbionts is accompanied by a transfer of sym32 from gastrodermal vesicles to the symbiosome membranes. This would most likely occur during phagocytic uptake of the symbiont, by fusion of the sym32 vesicles with the phagosome.

The presence of sym32 within the dinoflagellates them-

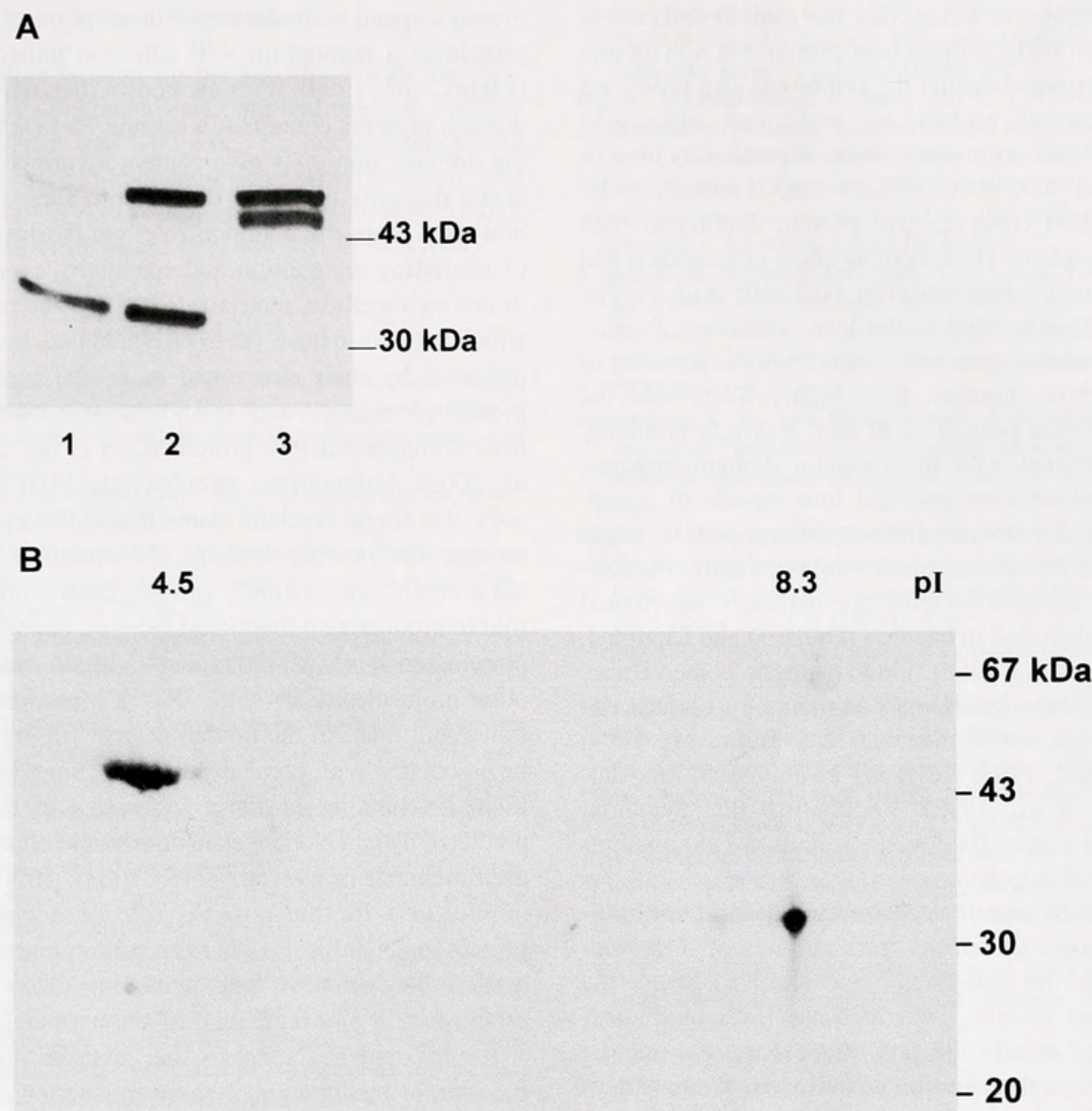


Figure 5. Anti-sym32 Western blots of protein homogenates from *Symbiodinium*. (A) Western blot of a one-dimensional gel. All lanes contained 10 μ g of soluble protein. Lane 1, host-only proteins, shows a 32-kDa band and a faint 48-kDa band. Lane 2, *Symbiodinium muscatinei* freshly harvested from a host anemone (and therefore contaminated with host tissues), shows three bands: a strongly staining 32-kDa band, a strongly staining 48-kDa band, and a faint 45-kDa band. Lane 3, cultured *Symbiodinium bermudense*, contains two equal intensity bands at 45-kDa and 48-kDa. (B) Western blot of a two-dimensional gel of protein homogenate (60 μ g) from *S. muscatinei* freshly harvested from an anemone host. Two spots are present: a 32-kDa, pI 8.2, spot, identifiable as sym32, presumably from contaminating host tissue, and a 48-kDa spot, pI range 4.3–4.5.

selves complicates the picture and adds a new dimension to our studies of sym32. The accumulation body in dinoflagellates is postulated to function as a lysosome, although this organelle has not been studied in many species, and its function has not been examined in *Symbiodinium*. The free-living dinoflagellate *Prorocentrum* has multiple accumulation bodies with features characteristic of eukaryotic lysosomes. These bodies contain electron-dense material, fibrous material, and membranous material, and they possess acid phosphatase activity, react positively with the periodic acid/Schiff reagent, and stain with acridine orange (Zhou and Fritz, 1994). *Symbiodinium* has a single accumulation body that varies in size and is postulated to function

as a molecular “trash dump” (Taylor, 1987; Wakefield *et al.*, 2000). We observed that the accumulation body is invariably located adjacent to the nucleus, often appearing to displace the edge of the nucleus. If the accumulation body is a lysosome or a trash dump, host sym32 may be transported from the vacuolar membranes, across the dinoflagellate cell wall, and into a degradative pathway within the dinoflagellate. This ability to transport molecules from the host cell, across the vacuolar membrane, into the cytosol or organelles of an intracellular inhabitant is common in parasitic protozoans, and there are many mechanisms by which this occurs (Schwab *et al.*, 1994; Raibaud *et al.*, 2001; Goodyer *et al.*, 1997).

It is also possible, however, that the protein detected in the accumulation body is not a host protein but a symbiont protein. To determine whether the symbionts also produce a sym32 cross-reactive protein, we performed anti-sym32 Western analysis on symbiont proteins separated by one- or two-dimensional SDS-PAGE. Anti-sym32 antiserum labeled a 45/48-kDa cross-reactive protein doublet in both cultured *S. bermudense* (free from any host cell contact) and *S. muscatinei* that we removed from host cells (Fig. 5). The presence of a 32-kDa band in the lane containing *S. muscatinei* proteins almost certainly results from the presence of contaminating host proteins. It is highly likely that the symbiont 45/48-kDa protein is, in fact, a sym32 homolog. Its size is consistent with the fasciclin domain proteins, which consist of between one and four repeats of an approximately 15-kDa domain (thus symbiont p45/48 might consist of three repeats of the 15-kDa-domain). Furthermore, fasciclin domain proteins are diversely distributed and have been identified in bacteria (Paulsrud and Lindblad, 2002; Terasaka *et al.*, 1989), photosynthetic algae (Huber and Sumper, 1994), invertebrate animals (Bastiani *et al.*, 1987; Zinn *et al.*, 1988; Brennan and Robinson, 1994; Bostic and Strand, 1996; Reynolds *et al.*, 2000), and humans (Skonier *et al.*, 1992). To confirm that symbiont p45/48 is in fact a fasciclin domain protein, we are attempting to sequence this gene.

We attempted to immunolocalize the 45/48-kDa symbiont protein in fixed specimens from cultures of *S. bermudense*, by using the anti-sym32 antiserum to detect the 45/48-kDa target protein. Two methods (immunofluorescence to examine intact cells, and immunoelectron microscopy to examine sectioned cells) failed to detect any pattern of staining. This suggests that the anti-sym32 antiserum, although able to recognize epitopes in denatured symbiont proteins on a Western blot (Fig. 4), was not specific enough to detect epitopes in the native protein within *S. bermudense* (data not shown). Occasionally, antibodies can work in Western analysis but not immunolocalization, especially when the antibody is being used to detect a protein other than that to which it was developed (Harlow and Lane, 1999). These results strengthen the conclusion that the protein that we observed within the symbiosome membranes and the symbiont accumulation body is the host-derived protein and not the symbiont-derived protein. If true, this indicates that the symbiont has an active role in modifying the structure or design of the symbiosome membranes. However, this possibility will remain untested until antibodies that can distinguish between the host and symbiont proteins are developed.

Interest in fasciclin domain proteins appears to be gaining momentum judging from the many recent reports that describe the functions or structures of these proteins in diverse organisms (for example, Kim *et al.*, 2002; Tamura *et al.*, 2002; Carr *et al.*, 2003; Clout *et al.*, 2003). These reports

greatly expand upon the initial description of the fasciclin I protein as a homophilic cell adhesion molecule in insects (Elkins *et al.*, 1990). It is now known that, while all fasciclin domain proteins contain at least one 15-kDa fasciclin binding domain, they may also contain a variety of other functional domains that lend diversity to their functions. All, however, share the common role, *via* the fasciclin domain, of mediating recognition and specificity events in cell-cell or cell-extracellular matrix interaction. The mechanisms by which they do so have yet to be elucidated, but clues may be provided by their structures, as in the insect fasciclin I protein (domains 3 and 4) and the *Mycobacteria tuberculosis* complex MBP70 protein (Carr *et al.*, 2003; Clout *et al.*, 2003). Although the mycobacterial MBP70 protein consists of a single fasciclin domain, and the insect fasciclin I protein contains four domains, the structures of the individual domains are strikingly similar. Each domain appears to fold to produce two functional faces on opposite sides of the protein, each of which probably binds independently to other molecules (Carr *et al.*, 2003). Mutations within these functional faces in the human protein β ig-h3 are known to be associated with corneal dystrophy, suggesting that specificity in binding of these molecules to their targets is mediated by small changes in amino acid composition along the functional faces (Carr *et al.*, 2003). This has important implications for the possible role of a fasciclin domain protein in a symbiosis, where specificity in molecular interactions between host and symbiont likely mediates the establishment and regulation of the partnership.

Recent evidence suggests that fasciclin domain proteins function in mediating symbiotic interactions in other associations. In both the rhizobium-plant association and the cyanobacterial-fungal lichen association, homologs have been identified from the symbiont genomes, and in plants, deletion of this gene reduces its ability to fix nitrogen (Oke and Long, 1999; Paulsrud and Lindblad, 2002). This is the first report to suggest that both partners in a symbiosis may produce fasciclin domain proteins.

The sym32 story is complex. The sym32 protein apparently has functions in multiple biological processes within the host; both in symbiotic interactions with dinoflagellates (as evidenced by the presence of sym32 within the membranes surrounding the dinoflagellates), and in other non-symbiosis-related processes (as evidenced by the presence of sym32 in the epidermis of both aposymbiotic and symbiotic anemones). Furthermore, the presence of a cross-reactive protein in both free-living *Symbiodinium* and *Symbiodinium* freshly isolated from a host suggests that the symbionts possess a sym32 homolog. Still to be elucidated are the degree to which the host and symbiont proteins interact and the roles that each plays in the biology of each partner separately and of the partners in symbiosis.

Acknowledgments

Thanks to Mike Nesson for his assistance with the electron microscopy, Santiago Perez for cultures of *Symbiodinium bermudense*, and Kim Koch for her assistance with the light-level immunocytochemistry. This research was supported by an EPA STAR graduate fellowship to JAS (915432) and an NSF award (9728405-IBN) to VMW.

Literature Cited

- Bastiani, M. J., A. L. Harrelson, P. M. Snow, and C. S. Goodman. 1987. Expression of fasciclin I and II glycoproteins on subsets of axon pathways during neuronal development in the grasshopper. *Cell* 48: 745–755.
- Batley, J. F., and J. S. Patton. 1987. Glycerol translocation in *Condylactis gigantea*. *Mar. Biol.* 95: 37–46.
- Bostic, J. R., and M. Strand. 1996. Molecular cloning of a *Schistosoma mansoni* protein expressed in the gynecophoral canal of male worms. *Mol. Biochem. Parasitol.* 79: 79–89.
- Brennan, C., and J. J. Robinson. 1994. Cloning and characterization of HLC-32, a 32-kDa protein component of the sea urchin extraembryonic matrix, the hyaline layer. *Dev. Biol.* 165: 556–565.
- Carr, M. D., M. J. Bloemink, E. Dentten, A. O. Whelan, S. V. Gordon, G. Kelly, T. A. Frenkiel, R. G. Hewinson, and R. A. Williamson. 2003. Solution structure of the *Mycobacterium tuberculosis* complex protein MPB70: from tuberculosis pathogenesis to inherited human corneal disease. *J. Biol. Chem.* 10.1074/jbc.M307235200.
- Clout, N. J., D. Tisi, and E. Hohenester. 2003. Novel fold revealed by the structure of a FAS1 domain pair from the insect cell adhesion molecule fasciclin I. *Structure* 11: 197–203.
- Colley, N. J., and R. K. Trench. 1983. Selectivity in phagocytosis and persistence of symbiotic algae by the scyphistoma stage of the jellyfish *Cassiopeia xamachana*. *Proc. R. Soc. Lond. B* 219: 61–82.
- Courret, N., C. Frehel, N. Gouhier, M. Pouchelet, E. Prina, P. Roux, and J. C. Antoine. 2002. Biogenesis of *Leishmania*-harbouring parasitophorous vacuoles following phagocytosis of the metacyclic promastigote or amastigote stages of the parasites. *J. Cell Sci.* 115: 2303–2316.
- Dobrowolski, J. M., and L. D. Sibley. 1996. *Toxoplasma* invasion of mammalian cells is powered by the actin cytoskeleton of the parasite. *Cell* 84: 933–939.
- Elkins, T., M. Hortsch, A. J. Bieber, P. M. Snow, and C. S. Goodman. 1990. *Drosophila* fasciclin I is a novel homophilic adhesion molecule that along with fasciclin III can mediate cell sorting. *J. Cell Biol.* 110: 1825–1832.
- Falkowski, P. G., Z. Dubinsky, and L. Muscatine. 1984. Light and the bioenergetics of a symbiotic coral. *Bioscience* 34: 705–709.
- Fitt, W. K., and R. K. Trench. 1983. Endocytosis of the symbiotic dinoflagellate *Symbiodinium microadriaticum* Freudenthal by endodermal cells of the scyphistomae of *Cassiopeia xamachana* and resistance of the algae to host digestion. *J. Cell Sci.* 64: 195–212.
- Goodyer, I. D., B. Pouvelle, T. G. Schneider, D. P. Trelka, and T. F. Taraschi. 1997. Characterization of macromolecular transport pathways in malaria-infected erythrocytes. *Mol. Biochem. Parasitol.* 87: 13–28.
- Hackstadt, T. 2000. Redirection of host vesicle trafficking pathways by intracellular parasites. *Traffic* 1: 93–99.
- Harboe, M., and S. Nagai. 1984. MPB70, a unique antigen of *Mycobacterium bovis* BCG. *Am. Rev. Respir. Dis.* 128: 444–452.
- Harboe, M., S. Nagai, H. G. Wilker, K. Sletten, and S. Haga. 1995. Homology between the MPB70 and MPB83 proteins of *Mycobacterium bovis* BCG. *Scand. J. Immunol.* 42: 46–51.
- Harlow, E., and D. P. Lane. 1999. Antibody-antigen interactions. Pp. 21–39 in *Using Antibodies: A Laboratory Manual*. Cold Spring Harbor Laboratory Press, Cold Spring Harbor, NY.
- Hu, S., M. Sonnenfeld, S. Stahl, and S. T. Crews. 1998. Midline fasciclin: a *Drosophila* fasciclin-I-related membrane protein localized to the CNS midline cells and trachea. *J. Neurobiol.* 3: 77–93.
- Huber, O., and M. Sumper. 1994. Algal-CAMs: isoforms of a cell adhesion molecule in embryos of the alga *Volvox* with homology to *Drosophila* fasciclin I. *EMBO* 13: 4212–4222.
- Kim, J.-E., H.-W. Jeong, J.-O. Nam, B.-H. Lee, J.-Y. Choi, R.-W. Park, J.-Y. Park, and I.-S. Kim. 2002. Identification of motifs in the fasciclin domains of the transforming growth factor- β -induced matrix protein β ig-h3 that interact with the α v β 5 integrin. *J. Biol. Chem.* 277(48): 46159–46165.
- LaJeunesse, T. C., and R. K. Trench. 2000. Biogeography of two species of *Symbiodinium* (Freudenthal) inhabiting the intertidal sea anemone *Anthopleura elegantissima* (Brandt). *Biol. Bull.* 199: 126–134.
- Lewis, D. H., and D. C. Smith. 1971. The autotrophic nutrition of symbiotic marine coelenterates with special reference to hermatypic corals. I. Movement of photosynthetic products between the symbionts. *Proc. R. Soc. Lond. B* 178: 111–129.
- Mellman, I. 1996. Endocytosis and molecular sorting. *Annu. Rev. Cell Dev. Biol.* 12: 575–625.
- Mukkada, A. J., J. C. Meade, T. A. Glaser, and P. F. Bonventre. 1985. Enhanced metabolism of *Leishmania donovani* amastigotes at acid pH: an adaptation for intracellular growth. *Science* 229: 1099–1101.
- Muller-Parker, G., and C. F. D'Elia. 1998. Interactions between corals and their symbiotic algae. Pp. 96–113 in *Life and Death of Coral Reefs*, C. Birkeland, ed. Chapman and Hall, New York.
- Muscatine, L. 1990. The role of symbiotic algae in carbon and energy flux in reef corals. Pp. 75–87 in *Coral Reefs*, Z. Dubinsky, ed. Elsevier, Amsterdam.
- Oke, V., and S. R. Long. 1999. Bacterial genes induced within the nodule during the *Rhizobium*-legume symbiosis. *Mol. Microbiol.* 32: 837–849.
- Paulsrud, P., and P. Lindblad. 2002. Fasciclin domain proteins are present in *Nostoc* symbionts of lichens. *Appl. Environ. Microbiol.* 68: 2036–2039.
- Raibaud, A., P. Lupetti, R. E. Paul, D. Mercati, P. T. Brey, R. E. Sinden, J. E. Heuser, and R. Dallai. 2001. Cryofracture electron microscopy of the ookinete pellicle of *Plasmodium gallinaceum* reveals the existence of novel pores in the alveolar membranes. *J. Struct. Biol.* 135: 47–57.
- Reynolds, W. S., J. A. Schwarz, and V. M. Weis. 2000. Symbiosis-enhanced gene expression in cnidarian-algal associations: cloning and characterization of a cDNA, sym32, encoding a possible cell adhesion protein. *Comp. Biochem. Physiol. A* 126: 33–44.
- Schwab, J. C., C. J. Beckers, and K. A. Joiner. 1994. The parasitophorous vacuole membrane surrounding intracellular *Toxoplasma gondii* functions as a molecular sieve. *Proc. Natl. Acad. Sci. USA* 91: 509–513.
- Schwarz, J. A., D. A. Krupp, and V. M. Weis. 1999. Late larval development and onset of symbiosis in the scleractinian coral *Fungia scutaria*. *Biol. Bull.* 196: 70–79.
- Schwarz, J. A., D. C. Potts, and V. M. Weis. 2002. Feeding behavior and acquisition of zooxanthellae by planula larvae of the sea anemone *Anthopleura elegantissima*. *Mar. Biol.* 140: 471–478.
- Sinai, A. P., and K. A. Joiner. 1997. Safe haven: the cell biology of nonfusogenic pathogen vacuoles. *Annu. Rev. Microbiol.* 51: 415–462.
- Skonier, J., M. Neubauer, M. Madisen, K. Bennet, G. Plowman, and A. F. Purchio. 1992. cDNA cloning and sequence analysis of β ig-h3, a novel gene induced in an adenocarcinoma cell line after treatment with transforming growth factor- β . *DNA Cell Biol.* 11: 511–522.

- Takeshita, S., R. Kikuno, K. Tezuka, and E. Amann. 1993. OSF-2: cloning and characterization of a novel protein expressed in bone with sequence homology to the insect protein fasciclin I. *Biochem J.* **294**: 271–278.
- Tamura, Y., H. Adachi, J. Osuga, K. Ohashi, N. Yahagi, M. Sekiya, H. Okazaki, S. Tomita, Y. Iizuka, H. Shimano, R. Nagai, S. Kimura, M. Tsujimoto, and S. Ishibashi. 2003. FEEL-1 and FEEL-2 are endocytic receptors for advanced glycation end products. *J. Biol. Chem.* **278**(15): 12613–12617.
- Taylor, D. L. 1968. *In situ* studies of the cytochemistry and ultrastructure of a symbiotic marine dinoflagellate. *J. Mar. Biol. Assoc. UK* **48**: 349–366.
- Taylor, F. J. R., ed. 1987. *The Biology of Dinoflagellates*. Botanical Monographs, Vol. 21. Blackwell Scientific Publications, Oxford.
- Terasaka, K., R. Yamaguchi, K. Matsuo, A. Yamazaki, S. Nagai, and T. Yamada. 1989. Complete nucleotide sequence of immunogenic protein MPB70 from *Mycobacterium bovis* BCG. *FEMS Microbiol. Lett.* **49**: 273–276.
- Wakefield, T. S., and S. C. Kempf. 2001. Development of host- and symbiont-specific monoclonal antibodies and confirmation of the origin of the symbiosome membrane in a cnidarian-dinoflagellate symbiosis. *Biol. Bull.* **200**: 127–143.
- Wakefield, T. S., M. A. Farmer, and S. C. Kempf. 2000. Revised description of the fine structure of *in situ* "Zooxanthellae" genus *Symbiodinium*. *Biol. Bull.* **199**: 76–84.
- Wang, J. T., and A. E. Douglas. 1998. Nitrogen recycling or nitrogen conservation in an alga-invertebrate symbiosis? *J. Exp. Biol.* **201**: 2443–2453.
- Wang, J. T., and A. E. Douglas. 1999. Essential amino acid synthesis and nitrogen recycling in an alga-invertebrate symbiosis. *Mar. Biol.* **135**: 219–222.
- Weis, V. M. 1993. The effect of dissolved inorganic carbon on the photosynthesis of the symbiotic sea anemone *Aiptasia pulchella*: role of carbonic anhydrase. *J. Exp. Mar. Biol. Ecol.* **174**: 209–225.
- Weis, V. M., and R. P. Levine. 1996. Differential protein profiles reflect the different lifestyles of symbiotic and aposymbiotic *Anthopleura elegantissima*, a sea anemone from temperate waters. *J. Exp. Biol.* **199**: 883–892.
- Weis, V. M., and W. S. Reynolds. 1999. Carbonic anhydrase expression and synthesis in the sea anemone *Anthopleura elegantissima* are enhanced by the presence of dinoflagellate symbionts. *Physiol. Biochem. Zool.* **72**: 307–316.
- Weis, V. M., J. von Kampen, and R. P. Levine. 1998. Techniques for exploring symbiosis-specific gene expression in cnidarian-algal associations. Pp 435–448 in *Some Molecular Approaches to the Study of the Ocean*, K. E. Cooksey, ed. Chapman and Hall, London.
- Zhou, J., and L. Fritz. 1994. The PAS/accumulation bodies in *Prorocentrum lima* and *Prorocentrum maculosum* (Dinophyceae) are dinoflagellate lysosomes. *J. Phycol.* **30**: 39–44.
- Zinn, K., L. McAllister, and C. S. Goodman. 1988. Sequence analysis and neuronal expression of fasciclin I in grasshopper and *Drosophila*. *Cell* **53**: 577–587.



Schwarz, J A and Weis, Virginia M. 2003. "Localization of a Symbiosis-Related Protein, Sym32, in the *Anthopleura elegantissima*-*Symbiodinium muscatinei* Association." *The Biological bulletin* 205, 339–350.

<https://doi.org/10.2307/1543297>.

View This Item Online: <https://www.biodiversitylibrary.org/item/17303>

DOI: <https://doi.org/10.2307/1543297>

Permalink: <https://www.biodiversitylibrary.org/partpdf/5923>

Holding Institution

MBLWHOI Library

Sponsored by

MBLWHOI Library

Copyright & Reuse

Copyright Status: In copyright. Digitized with the permission of the rights holder.

Rights Holder: University of Chicago

License: <http://creativecommons.org/licenses/by-nc-sa/3.0/>

Rights: <https://biodiversitylibrary.org/permissions>

This document was created from content at the **Biodiversity Heritage Library**, the world's largest open access digital library for biodiversity literature and archives. Visit BHL at <https://www.biodiversitylibrary.org>.