Effects of colonization, luminescence, and autoinducer on host transcription during development of the squid-vibrio association

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The light–organ symbiosis between the squid *Euprymna scolopes* and the luminous bacterium *Vibrio fischeri* offers the opportunity to decipher the hour-by-hour events that occur during the natural colonization of an animal's epithelial surface by its microbial partners. To determine the genetic basis of these events, a glass-slide microarray was used to characterize the light-organ transcriptome of juvenile squid in response to the initiation of symbiosis. Patterns of gene expression were compared between animals not exposed to the symbiont, exposed to the wild-type symbiont, or exposed to a mutant symbiont defective in either of two key characters of this association: bacterial luminescence or autoinducer (AI) production. Hundreds of genes were differentially regulated as a result of symbiosis initiation, and a hierarchy existed in the magnitude of the host's response to three symbiont features: bacterial presence > luminescence > AI production. Putative host receptors for bacterial surface molecules known to induce squid development are up-regulated by symbiont light production, suggesting that bioluminescence plays a key role in preparing the host for bacteria-induced development. Further, because the transcriptional response of tissues exposed to AI in the natural context (i.e., with the symbionts) differed from that to AI alone, the presence of the bacteria potentiates the role of quorum signals in symbiosis. Comparison of these microarray data with those from other symbioses, such as germ-free/conventionalized mice and zebrafish, revealed a set of shared genes that may represent a core set of ancient host responses conserved throughout animal evolution.

Euprymna | fischeri | microarray | symbiosis

Among the most common beneficial microbial associations are those between bacteria and the host epithelia they colonize. In many associations, a complex program of tissue adaptation and development is triggered by the presence of the symbionts (1–3); however, the nature of these programs and how they lead to the initiation of persistent beneficial relationships are poorly understood. Such knowledge is a vital part of understanding both how animals achieve a healthy state and how an invasion by pathogens compromises its maintenance. To address these questions, biologists are using a variety of vertebrate and invertebrate model systems that each reveals insights into a different aspect of host–bacteria interaction, such as cell–cell signaling, development, and immune response (4–10). Comparative studies among these various associations have had three broad goals: (*i*) to determine traits that are shared across the animal kingdom, (*ii*) to identify the factors driving the diversification of specific symbioses, and (*iii*) to define the principal differences between how the host interacts with a beneficial partner and with a pathogen. Recent progress toward these goals has followed technological advances on a number of fronts, including the creation of bioinformatics tools for inferring the composition and activities of a host's microbial partners (11, 12). In addition, genome-wide analyses of host gene expression during the development of an association have revealed the number and identities of genes that are differentially regulated in the formation of a successful, stable interaction at the epithelium–bacteria interface (5, 13).

The symbiotic association between the Hawaiian squid *Euprymna scolopes* and the luminous bacterium *Vibrio fischeri* has served as a useful model to analyze the onset and maintenance of a natural host–microbe relationship (10, 14). In this association, *V. fischeri* occurs as a monoculture growing along the apical surfaces of the epithelia that line crypts located deep within the squid's light-emitting organ. The nascent light organ of a newly hatched juvenile squid is free of symbionts (or "aposymbiotic") and, while being exposed to the hundreds of bacterial species present in seawater, becomes colonized only by *V. fischeri*. Despite this specificity, the association is initiated within minutes of hatching as bacteria within the seawater begin to gather in host-derived mucus shed by the superficial epithelia of the organ. Three to four hours later the amassed *V. fischeri* cells migrate to pores on the organ's surface, travel up cilia-lined ducts, and enter the blind-ended crypts. Interaction with the bacteria also induces development of host tissues: most notably, at ≈12 h after inoculation, the symbionts trigger the irreversible loss of the superficial epithelium (Fig. 1), with which they are not in direct contact. The regression of this epithelium involves a series of events, including the trafficking of macrophage-like cells into the tissue, apoptosis of the epithelial cells, and an eventual sloughing of these cells. This extensive morphogenesis is mediated by molecules released by the symbionts, including the lipid A component of LPS and the tetrapeptide monomer of peptidoglycan (PGN), two derivatives of the bacterial cell envelope (10, 14). In addition, the symbionts induce changes in the host cells with which they directly associate (Fig. 1); specifically, they induce a swelling of the crypt epithelial cells and an increase in the density of their microvilli (10).

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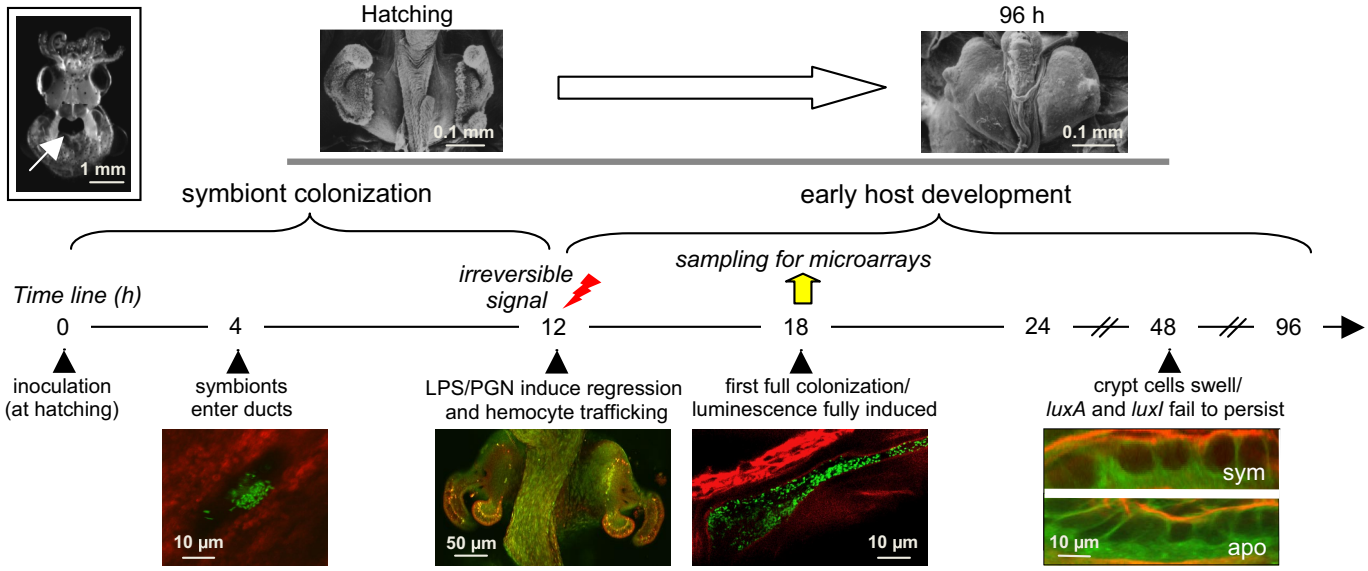

Fig. 1. Features of early host development in the squid-vibrio symbiosis. The light-organ tissues undergo a series of symbiont-induced developmental events (see text for details), here visualized by scanning electron microscopy (*Upper*) and confocal microscopy (*Lower*). After aggregating in host mucus, at 4 h, GFP-labeled *V. fischeri* cells (green) enter host tissues (red). At 12 h, the symbionts induce the loss of the superficial ciliated epithelium that facilitates colonization, a process that is complete by 96 h. By 18 h, the time when host transcriptional responses were characterized, bacteria fill the epithelium-lined crypts (red) and are highly luminous. By 48 h, symbionts induce crypt-cell swelling, a phenotype that is not observed in colonizations by *luxA* and *luxI* mutants, and that correlates with their inability to persist.

In this symbiosis, the only known contribution of the bacteria is luminescence (15), which is mediated by quorum signaling, a cell–cell sensing mechanism by which beneficial and pathogenic bacterial species coordinately control gene expression in a cell-density-dependent manner (16). *V. fischeri* cells do not induce luminescence until ≈8 h after inoculation. By then, the accumulation of the second of two *V. fischeri*-produced quorum signals (17), the 3-oxohexanoyl-L-homoserine lactone autoinducer (AI) molecule, leads to the full induction of the lux operon, which encodes the light-emitting enzyme subunits of luciferase (LuxA and LuxB) and the AI synthase (LuxI) (18). The ability to produce both luciferase and AI is critical to the symbiosis; mutants defective in either of these factors fail to induce crypt cell swelling or to persist normally in the light organ beyond 24 h. Interestingly, colonization by a *luxA* (but not a *luxI*) mutant additionally fails to induce either proper hemocyte trafficking or regression of the superficial epithelium (19). This differential response may reflect that (*i*) the *luxA* mutant (unlike the *luxI*) produces AI, and/or (*ii*) the *luxI* mutant (unlike the *luxA*) still produces a small amount of luminescence (18). Thus, to fully understand the mechanisms that trigger these developmental events (Fig. 1), we must determine how each of these two consequences of symbiotic colonization, luminescence and AI production, differentially affects the host.

We hypothesized that the dramatic developmental events that occur in response to colonization would be reflected in underlying transcriptional changes in host light-organ tissues. The recent construction of an *E. scolopes* light-organ-derived EST database, consisting of a set of 13,962 unique sequences (20), led to the design of a glass-slide microarray for the study of global changes in host-gene expression during symbiosis. We used this microarray to characterize and separate the host's transcriptional response to the presence of three components of the symbiosis: bacterial symbionts, luminescence, and AI. Patterns of light-organ gene expression were determined 18 h after inoculation of juvenile squid, when all of the conspicuous symbiont-induced developmental programs have been triggered, and the bacterial partners have fully colonized the organ and are producing maximal levels of luminescence.

Results

Hierarchical Host Transcriptional Responses to Symbiont Colonization. To reveal broad patterns of gene expression that result from interaction with the symbiont, we analyzed eight individual comparisons of colonization treatments, as well as three comparisons of larger groupings of general colonization conditions, or "grouped conditions": with/without symbionts, with/without luminescence, or with/without AI (Table 1). All comparisons were based on four independent biological replicates of each colonization treatment [see supporting information (SI) *Text* for details]. Two lines of evidence support a hierarchy among the grouped conditions; bacterial presence itself had the greatest effect, followed by symbiont light production, and then AI production. This evidence includes: (*i*) the topology of a microarray condition tree (Fig. 2), which was derived from the expression levels of 781 differentially regulated genes in all individual comparisons of colonization treatments; and (*ii*) the frequency and patterns of differential gene regulation in individual and specific grouped conditions (Tables 1, 2, S1, and S2). In addition, the reliability of these microarray expression results was confirmed by quantitative real-time PCR (QRT-PCR) analysis (*SI Text*). Nine of the 10 genes analyzed were differentially regulated in both the same direction and magnitude as predicted from the array data (Table S3).

Analysis of the Condition Tree. To examine the overall clustering of the gene expression data among treatments, we created a condition tree (Fig. 2) based on the average expression values ($n = 3$) of the 781 unique differentially expressed transcripts in the individual comparisons (Tables 1 and S4). The two aposymbiotic conditions (Apo and Apo + AI) clustered separately from all of the symbiotic conditions. They also clustered separately from each other, indicating that the transcriptional profile is significantly affected by AI addition, even in the absence of symbionts. The transcriptional profiles of all symbiotic light organs clustered together. However, organs not exposed to luminescence (i.e., animals colonized by the *luxA* mutant) had expression profiles that clustered separately from those that were exposed. Based on this indication of the impact of luminescence, we predicted that the transcriptional profile derived

Table 1. Numbers of light-organ transcripts differentially regulated between conditions

Comparisons	Total number of transcripts*	Number of transcripts differentially regulated ≥ 2-fold						
		Total	Up†	Down†	Known‡	Unknown/Hypo‡	No hits‡	Expression class§
Grouped conditions¶								
Symbionts vs. no symbionts	132	70	33	37	42	8/8	12	N
Light vs. no light	27	19	15	4	9	5/2	3	P
AI vs. no AI	10	10	10	0	5	3/1	1	O
Individual conditions								
Wild type vs. apo	462	262	141	121	145	45/31	41	A, B, D, E
Wild type vs. *luxA*	211	149	96	53	57	54/1	37	D, E, F, G
Wild type vs. *luxI*	131	99	50	49	37	36/0	26	B, C, E, F
Wild type vs. *luxI* + AI	24	24	9	15	8	2/12	2	Q
Apo vs. apo + AI	13	2	2	0	1	1/0	0	H
Apo vs. *luxI*	154	94	57	37	56	17/9	12	K, L
Apo + AI vs. *luxI* + AI	148	89	55	34	51	16/9	13	L, M
luxI vs. *luxI* + AI	32	16	11	5	5	1/5	5	I, J

*Transcripts significantly differentially regulated between conditions (see *Methods*); total number of unique transcripts for all grouped conditions, 145; total number for all individual conditions, 781.

†Those transcripts up- or down-regulated ≥2-fold, calculated as the first condition over the second.

‡Known, related to a described gene; unknown/hypo, undescribed or hypothetical protein; no hits, no significant homology to the nonredundant database of Genbank, as determined by BLASTX analysis.

§Letter designation indicates the expression class in Fig. S1 and/or Table S5.

¶Differences between conditions sharing the same category of exposure condition. "Symbiont" includes wild type, *luxI*, *luxI* + AI and *luxA*; "no symbiont" includes apo and apo + AI; "light" includes wild type, *luxI* + AI; "no light" includes apo, apo + AI and *luxA*; "AI" includes wild type, apo + AI, *luxI* + AI and *luxA*; and, "no AI" includes apo and *luxI*.

from *luxI* + AI (bright luminescence) would more closely resemble that of wild type (bright) than that of *luxI* (dim) (18). However, the individual profiles of light organs colonized by *V. fischeri* producing any luminescence (wild type, *luxI*, and *luxI* + AI) did not resolve with high confidence (Fig. 2). Two conclusions arise from these data: (*i*) even the low levels of light emission produced by the *luxI* mutant are sufficient to trigger much of the host's symbiotic response to luminescence, and (*ii*) the presence of luminescence has a greater influence on the transcriptional profile of the juvenile light organ than does the presence or absence of AI.

Frequency and Patterns of Differential Gene Regulation. The relative number (Table 1), as well as the fold change (Tables 2 and S2), of differentially regulated transcripts among the grouped conditions

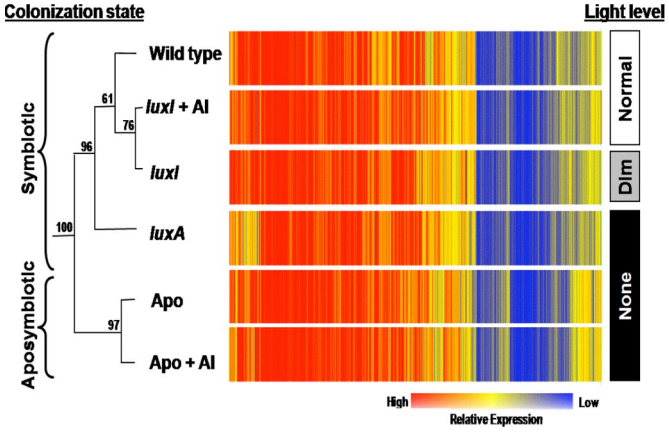

Fig. 2. Transcriptional profiles of light organs exposed to different colonization conditions. Juvenile squid were either left uninoculated (apo) or inoculated with wild-type, *luxA*, or *luxI* strains of *V. fischeri*, in the presence or absence of added AI. The relative similarities of patterns of gene expression under the different conditions were mapped by using change correlation average linkage. Numbers at the nodes represent percent confidence from bootstrapping analysis (n = 1,000). The relative levels of luminescence produced in the light organs under each condition are also indicated.

was also consistent with the dominance hierarchy of: the presence of bacteria > luminescence > AI. This hierarchical relationship was further supported by a three-way Venn diagram comparison, in which we characterized the patterns of differential gene expression during *V. fischeri* colonization with (*i*) both luminescence and AI present (wild type vs. Apo), (*ii*) luminescence present but no AI (wild type vs. *luxI*), and (*iii*) AI present but no luminescence (wild type vs. *luxA*) (Fig. S1*A* and Table S5 *A–G*).

We also did two pair-wise comparisons to determine the influence of colonization state on responses to AI. We first compared {Apo vs. Apo + AI} with {*luxI* vs. *luxI* + AI} to assay the effects of AI irrespective of colonization (Fig. S1*B*; Table S5 *H–J*). If the presence of the bacterial colonization were not required for the light organ to respond to AI, we would expect a similar result from these two comparisons. However, more than twice the number of transcripts were differentially regulated when AI was added in the presence of *V. fischeri* cells than in their absence, and only one transcript, annotated as "unknown," was shared. Therefore, the host tissue naturally responds to the presence of AI only in the biologically relevant condition of the presence of symbionts. This tissue response may work indirectly through the activity of AI on another bacterial activity(s). The second pair-wise comparison, {Apo vs. *luxI*} and {Apo + AI vs.

Table 2. Transcripts regulated by all three conditions

Annotation of transcript	Fold change*		
	S/NS	L/NL	A/NA
Require symbionts with luminescence and AI			
LPS-binding protein	8.6	4.4	3.4
Peptidoglycan recognition protein 1	7.3	4.7	2.2
Galaxin-1 (unknown function)	4.8	3.3	2.6
Galaxin-2 (unknown function)	4.1	2.9	2.2
Tetraspanin 3 (membrane trafficking)	2.2	1.9	1.5

Complete list in Table S2, including transcripts regulated by only one or two of the conditions

*Calculated as the first condition relative to the second; S/NS, symbionts vs. no symbionts; L/NL, light vs. no light; or A/NA, AI vs. no AI (e.g., Table 1).

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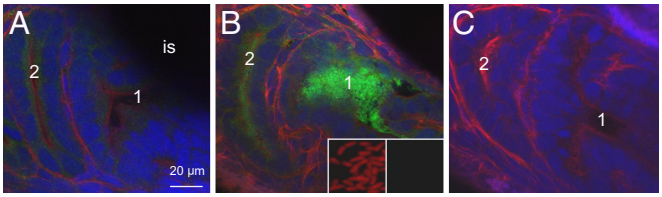

Fig. 3. Localization of EsLBP in juvenile light-organ crypts using confocal immunocytochemistry (ICC) (36). (*A*) In aposymbiotic animals, FITC-labeled secondary antibodies localized EsLBP (green) to the apical surfaces of the crypt epithelia. (*B*) In symbiotic animals, the epithelia remained labeled; however, a large amount of labeling had appeared in the crypt spaces as well. The staining was not the result of *V. fischeri* cells directly binding the EsLBP antibody. (*Inset*) When these bacteria (≈1 μm), counterstained with propidium iodide (red; *Left* of *Inset*), were treated with the EsLBP antibody, there was no binding (*Right*). (*C*) Preimmune controls of both aposymbiotic and symbiotic crypts showed no nonspecific staining. In all images, counterstaining of animal tissues included TOTO3 (blue), which labels nucleic acids; and rhodamine phalloidin (red), which labels filamentous actin. Numbering indicates the two largest of the three crypts in each image; ''is'' indicates the ink sac. See details in *SI Text*.

luxI + AI} (Fig. S1*C*; Table S5 *K–M*) allowed an analysis of the effect of AI on the light organ's transcriptional response to the presence (or absence) of a bacterial colonization. There was an 80% overlap in the identity of the differentially regulated genes, reinforcing the notion that the presence of the bacteria is the most significant driving force in the alteration of gene expression during symbiosis. We were unable to perform a similarly detailed analysis of the role of luminescence, because it was not technically feasible to introduce light to the crypt epithelium in the absence of symbionts.

Regulation of Specific Genes and Response Pathways. The presence of the symbiont and the production of luminescence were expression classes with patterns of gene regulation of particular interest. Approximately one-third of the transcripts regulated solely by the presence of symbionts were either directly associated with signal-transduction pathways (13%) or were transcription factors (20%) (Table S5*A*). Of special significance was the differential regulation of transcripts encoding proteins typically associated with the responses of animals to bacterial infection. These proteins include receptors and other components of immune-related response systems, such as the NF-kappaB and MAP-kinase pathways (21), as well as components of the Kruppel-like factor regulatory cascade (22). For example, the presence of symbionts up-regulates genes encoding a putative host LPS-binding protein [*E. scolopes* LBP or EsLBP (20)] and PGN-recognition proteins (EsPGRP1 and EsPGRP2), as well as elements of both the NF-kappaB pathway (I-kappaB, I-kappaB kinase-gamma, and I-kappaB-zeta variant 3) and its associated proteasome-ubiquitin pathway (e.g., proteasome subunits, ubiquitin ligases, cullin-3). Because derivatives of LPS and PGN act as symbiont-derived morphogens that trigger host development (14), it is not surprising that expression of the putative receptors for these ligands, as well as components of their downstream response pathways, are regulated by the presence of bacterial colonization. To investigate whether such differential gene regulation would correspond to changes in encoded-protein production, we localized EsLBP within juvenile tissues in response to symbiont colonization (Fig. 3). The pattern of cross-reactivity of antibodies to this protein was markedly different between 18-h apo- and symbiotic animals in two ways. First, under either condition, antibody labeling occurred along the apical surfaces of the crypt epithelia; however, in symbiotic animals, strong labeling was also present within the crypt spaces that housed the colonizing symbionts. Second, the overall amount of labeling in the tissues was greater in symbiotic animals, correlating to the increased transcription of EsLBP (Tables 2 and S3).

In contrast to the above-described patterns of gene up-regulation, many transcripts encoding orthologs of proteins involved in the synthesis and maintenance of ciliated surfaces (e.g., orthologs of dynein isoforms and of rootletin) were down-regulated in response to the presence of symbionts. This decrease in transcript level occurs concomitantly with a major developmental event: the bacteria-triggered loss of the light organ's superficial ciliated epithelium (10), a structure that plays an important role in the initial stages of colonization. Interestingly, several transcripts that are likely to encode proteins associated with the visual transduction cascade (e.g., orthologs of the eye-specific retinal-binding protein, guanylate cyclase-1, and guanylate cyclase activator 1A) were also differentially regulated. The expression of these genes, as well as other orthologs encoding proteins of visual transduction, in the tissues of the juvenile light organ was first reported in the recent analyses of the *E. scolopes* EST database (20) and may indicate a mechanism by which the light organ perceives the level of bacterial luminescence. These microarray results suggest that the expression of the visual transduction transcripts is a response to the presence of symbionts and not a direct response to their luminescence, because the regulation was similar between juveniles colonized by the wild type and the nonluminous *luxA* mutant.

In addition to these effects of the presence of the symbionts, the Venn diagram analyses indicated that luminescence specifically induces the differential regulation of a number of host genes (Fig. S1*A*). One transcript, encoding the oxygen-carrying blood pigment hemocyanin (23), exhibited a remarkable pattern of differential regulation that suggests a clear significance to the symbiosis. The levels of hemocyanin transcript appear the same in both aposymbiotic animals and animals colonized by wild-type *V. fischeri* (Table S5*G*); however, animals colonized by the *luxA* mutant showed a dramatic down-regulation in hemocyanin transcript level. These data suggest that, when colonized by a nonluminous mutant of *V. fischeri*, the host responds by reducing the transport, and perhaps availability, of oxygen in the light organ, thereby sanctioning a defective symbiont (18).

Shared Symbiont-Induced Genes Among Animal Hosts. Whereas global gene regulation in the host during pathogenesis has been extensively documented (reviewed in ref. 24), there are only a few studies of the responses of animal tissues to interactions with beneficial microbial partners (5, 13, 25, 26). Gordon and coworkers (5) have previously determined that 59 differentially regulated transcripts of known annotation are shared between two distantly related vertebrates, zebrafish and mouse, in studies of the response of the gut epithelia to colonization by their normal microbiota. Of these 59 transcripts, the EST database of the squid light organ contains 45 genes that are either orthologs or in a shared gene family (Table S6). Our BLASTX analyses suggest that the other 14 genes are specific to vertebrates and their relatives. Interestingly, 16 of the 45 transcripts (5 orthologs and 11 in a shared gene family) were also differentially regulated among the 462 transcripts expressed differently between symbiotic and aposymbiotic light organs (Tables S4, S6, and S7). This differential regulation of the shared genes is highly significant ($P = 3.3 \times 10^{-7}$ by Fisher's Exact test; $P = 1.2 \times 10^{-10}$ by χ^2 test) (*SI Text*). Recent studies of the host transcriptome changes in *Yersinia enterocolitica* pathogenesis (27) have similarly demonstrated differential regulation of several of these genes (Table S7).

Discussion

Host Transcriptional Responses to Colonization by Wild-Type, *luxA*, and *luxI* Symbionts. Unique to this study is the comparison of host responses to either wild-type symbionts or isogenic symbionts defective in characters known to be essential for a persistent symbiosis, i.e., light production (*luxA*) and AI quorum sensing

(*luxI*) (18). The differences in induction of host transcriptional responses shared by these two mutants compared to wild-type symbionts (Fig. S1) are likely to reflect those genes involved in regulating events like crypt cell swelling and bacterial persistence, phenotypes that are defective in both these mutants (18). In contrast, the greater extent of host differential gene regulation in the *luxA* compared to the *luxI* mutant (Table S1) is likely to reflect host phenotypes like hemocyte trafficking and regression of the superficial epithelial field that are defective only in the *luxA* mutant (19). The different timing of the onset of these host phenotypes (Fig. 1) may correlate to the presence or absence of luminescence in the two mutants (Fig. 2).

How might differences in the host's transcriptional response to the *luxA* mutant underlie the inability of this strain to trigger normal light-organ morphogenesis? The absence of symbiont luminescence results in a 4- to 5-fold lower level of transcription of a putative LPS-binding protein and a PGN-recognition protein (Table 2). Further research will be required to demonstrate unequivocally that these specific proteins are the receptors for derivatives of *V. fischeri* LPS and PGN. Nevertheless, they are orthologs of receptors that sense these bacterial molecules, which are morphogens that signal light-organ development (10, 14). Thus, symbiont light production, which occurs at low to normal levels in *luxI* and wild-type strains (Fig. 2), appears to be coupled to the induction of receptors for these symbiont signals. These signals would then mediate morphogenesis of the epithelial surface. Such a coupling would provide a feed-forward response to the developing symbiosis. Also, nonluminous symbionts are delayed in triggering light-organ morphogenesis and may be eliminated before they can mediate the complete regression of host tissues that facilitate colonization (10). As such, the animal would remain receptive to inoculation by a subsequent *V. fischeri* strain that is luminescent. Interestingly, the small amount of luminescence of the *luxI* mutant seems to be sufficient to induce aspects of normal early development (e.g., hemocyte trafficking) but does not rescue the persistence defect, which appears later (18). Whether the second *V. fischeri* AI (17) also contributes to the triggering of these (or other) events in host development remains to be determined.

Does the host respond to symbiont light emission itself or to the lowering of the ambient oxygen concentration resulting from the strong oxygenase activity of the luminescent reaction? One hypothesis is that sensory proteins located in the organ (unpublished data) and encoded by orthologs of genes of the visual transduction cascade (20) are involved in the perception of bacterial luminescence, i.e., a direct mechanism to detect the presence of nonluminous "cheaters" (28). Alternatively, a differential regulation of host genes involved in oxygen utilization might indicate that the animal responds to the marked difference in oxygen utilization by wild-type and *luxA* symbionts (28). In regard to the latter hypothesis, it is interesting to note that a dramatic down-regulation of the gene encoding the host's blood pigment, hemocyanin, occurs during colonization by the *luxA* mutant (Tables S3 and S3). Thus, some portions of the host's responses to *luxA* symbionts may reflect a failure to provide normal oxygen levels to the light organ, affecting both tissue development and the bacterial population.

The transcriptional response to AI addition, in the presence or absence of bacterial symbionts, provides evidence that host tissues react differently to this signal molecule depending on whether they are colonized. These data reinforce the idea that the presentation of chemical signals and other effectors in the absence of the natural bacteria–host context can lead to different and potentially misleading molecular responses (27). In the squid-vibrio system, the host's response to AI is quite limited when compared with that evoked by the presence of either the bacteria themselves or their light production (Table S1). Although the small number of genes that are directly regulated by AI may play an important role, this study suggests that quorum signaling is a conversation held principally among the bacterial symbionts and the host's response appears largely to be mediated indirectly, i.e., through the effects of AI on the activities of the colonizing bacteria, such as luminescence. Because little overlap was observed between the genes regulated by luminescence and those regulated by AI (Figs. 2 and S1*A*), the host's perception of a defect in the *luxI* strain is likely to be independent of its attenuated level of light production. Instead, we propose that the differential between the host's response to wild-type and *luxI* symbionts is due to the activities of other, nonlux, *V. fischeri* genes that are regulated by AI (ref. 29; data not shown).

Similar Transcriptional Responses to Bacterial Symbionts Among Different Animal Hosts. The magnitude of the differential transcriptional regulation (i.e., hundreds of genes) that characterizes the interaction of *E. scolopes* with its symbionts is similar to that reported in other microarray studies of both pathogenic and beneficial animal–bacterial interactions (e.g., refs. 5, 13, 27). Thus, the transcriptional studies presented here not only provide a rich dataset that will inform further characterization of the squid-vibrio symbiosis but also add to a growing database defining the genomic responses of host organisms to their bacterial associates, regardless of the nature of the relationship.

The host squid's transcriptional responses identified here offer an opportunity to determine bacteria-induced changes in gene expression that are either specific to, or conserved across, different taxa of the animal kingdom. These shared changes in gene expression and possible functional pathways may represent a core set of host responses to the extracellular colonization of the apical surfaces of polarized epithelia. For example, a closer study of the 16 differentially regulated genes shared in the mouse, zebrafish, and squid symbioses reveal several associated with the immune response, including components involved in the NF-kappaB and oxidative stress pathways (Table S7). These data support the idea that this response, rather than being entirely devoted to self/nonself recognition, is a principal mechanism by which host animals control responses to bacteria, whether they are persistent beneficial partners or harmful pathogens (30, 31). In addition, an examination of the annotated portion of the total 781 differentially regulated transcripts (Table S4) suggests a pivotal role for three transcription factors that may work alone or coordinately in the control of epithelium–bacteria interactions: NF-kappaB, the ETS family, and the Kruppel-like family. ELF3, an ETS-family transcription factor (Table S2), is specific to epithelial cells, and mutations in this gene have been implicated in abnormal development of intestinal epithelia and in cancer (32, 33). Relevant here is that a recent study of host infection by uropathogenic *Escherichia coli* (UPEC) revealed that the gene encoding ELF3 is differentially regulated by the pathogen and suggested a link between epithelial differentiation and the proinflammatory response (34). Similarly, Kruppel-like transcription factors (Table S4) are also implicated in host responses, often mediating bacteria-induced changes in the host cytoskeleton (22, 34). The observation that these three transcription factors are differentially regulated in a wide variety of bacterial associations suggests they and their targets may be essential players in the control of epithelial colonization, regardless of the type of symbiosis.

As in our study, most of the attention to differentially regulated transcripts has in the past focused on genes whose functions can be inferred from annotated orthologs. However, as microarray-based transcriptional information becomes available for other symbiotic systems, a comparison of these databases may reveal certain "hypothetical" genes that commonly respond to bacterial colonization. Such an analysis could identify novel host transcripts that might play a conserved role in the maintenance of beneficial interactions with bacteria.

This study of the patterns of host transcriptional responses in the squid-vibrio symbiosis has produced a wealth of hypothesis-generating information. The data present a "snapshot" view of the host transcriptome at 18 h postinoculation, a critical time in the

trajectory of symbiotic development, and serve as a foundation for future characterizations of the events that precede and follow. As in most other such studies, these results represent an averaging of the transcriptional changes across a set of tissues. A more precise understanding of these changes at the tissue and cellular level will come from the localization of the expression of specific genes and gene-products by *in situ* hybridization and immunocytochemistry (e.g., refs. 35, 36). Such approaches may, for example, reveal that both the crypt epithelia, which are interacting directly with the symbionts, and the superficial epithelia, which are induced to regress (Fig. 1), exhibit significant differences in their patterns of gene expression that reflect the distinct developmental fates of these two tissues.

Whereas by 2005, dozens of microarray studies had been performed to describe host responses to pathogens (24), to date only a few have characterized transcriptional regulation in the interactions of animals with their normal microbiota. Thus, an understanding of genome-wide responses between animals and their coevolved microbial partners is still in its infancy. With the growing awareness that such associations are the most prevalent type of bacteria-host interaction, similar analyses of other systems promises an exciting horizon for the study of how animals and bacteria form and maintain long-term, mutually beneficial alliances.

Methods

Squid Colonization Experiments. Juvenile animals were collected within minutes of hatching and transferred to glass vials containing 2 ml of Hawaiian offshore seawater (HOSW). HOSW contains a natural assemblage of many kinds of marine bacteria, but has an insufficient number of *V. fischeri* to initiate light-organ colonization (10). A subset of juveniles was provided with no *V. fischeri* inoculum, i.e., were maintained aposymbiotic (apo), whereas the rest were made symbiotic by the addition of either wild-type *V. fischeri* ES114 (11), or *luxI* or *luxA* mutants of this strain (18). In all cases, symbiosis was initiated by placing the juveniles in vials containing 1,000 cells of the inoculating strain per milliliter of HOSW. After 6 h, all of the squid were transferred to fresh vials containing 2 ml of uninoculated HOSW; in some treatments, the vials contained an addition of 5 μM synthetic AI (Sigma-Aldrich).

Preparation of Light-Organ Tissues for Microarray Analyses. Six experimental treatments of juvenile animals were performed for the microarray matrix: uncolonized (Apo); uncolonized, but supplemented with AI (Apo + AI); colonized by wild-type *V. fischeri* (wild type); colonized by a mutant defective in luciferase synthesis (*luxA*); colonized by a mutant defective in AI synthesis (*luxI*); and, colonized by the *luxI* mutant, but supplemented with AI (*luxI* + AI) (Figs. 2 and S2 and S3). At 18 h postinoculation, animals were anesthetized in 2% ethanol in HOSW, and the light organs were removed into RNAlater (Ambion Biosystems). See *SI Text* for details.

Microarray Hybridizations and Analyses. Spotted glass microarrays (GLP3825) were prepared from a nonredundant cDNA library containing 13,962 sequences, obtained from 0- to 48-h postinoculation juvenile squid light organs as described (20). Each spotted-array experiment was performed with 1 μg of total RNA. In addition to three biological replicates of the six treatment conditions described above, dye-swap replicates and two on-chip replicates (for a total of at least four technical replicates/treatment) were performed for each treatment condition.

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