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Published in:
Biological Bulletin

DOI:
10.1086/695689

Publication date:
2017

Document version
Publisher's PDF, also known as Version of record

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Citation for published version (APA):
Chan, B. K. K., Sari, A., & Høeg, J. T. (2017). Cirripede Cypris Antennules: How Much Structural Variation Exists Among Balanomorphan Species from Hard-Bottom Habitats? Biological Bulletin, 233(2), 135-143. https://doi.org/10.1086/695689
Cirripede Cypris Antennules: How Much Structural Variation Exists Among Balanomorphan Species from Hard-Bottom Habitats?

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Abstract. Barnacle cypris antennules are important for substratum attachment during settlement and on through metamorphosis from the larval stage to sessile adult. Studies on the morphology of cirripede cyprids are mostly qualitative, based on descriptions from images obtained using a scanning electron microscope (SEM). To our knowledge, our study is the first to use scanning electron microscopy to quantify overall structural diversity in cypris antennules by measuring 26 morphological parameters, including the structure of sensory organs. We analyzed cyprids from seven species of balanomorphan barnacles inhabiting rocky shore communities; for comparison, we also included a sponge-inhabiting balanomorphan and a verrucomorphan species. Multivariate analysis of the structural parameters resulted in two distinct clusters of species. From nonmetric multidimensional scaling plots, the sponge-inhabiting Balanus spongicola and Verruca stroemia formed one cluster, while the other balanomorphan species, all from hard bottoms, grouped together in the other cluster. The shape of the attachment disk on segment 3 is the key parameter responsible for the separation into two clusters. The present results show that species from a coastal hard-bottom habitat may share a nearly identical antennular structure that is distinct from barnacles from other habitats, and this finding supports the fact that such species also have rather similar reactions to substratum cues during settlement. Any differences that may be found in settlement biology among such species must therefore be due either to differences in the properties of their adhesive mechanisms or to the way that sensory stimuli are detected by virtually identical setae and processed into settlement behavior by the cyprid.

Introduction

Barnacles are sessile marine organisms that occupy a vast range of marine habitats ranging from the coastal zone to the deep sea; and the species comprise well-known suspension feeders, numerous epibionts on a wide range of host organisms, and some of the most advanced parasites known from Metazoa (Anderson, 1994; Høeg and Møller, 2006; Rees et al., 2014). All barnacles have free-swimming larvae, and settlement is accomplished by the highly specialized cyprid larval stage (Walker et al., 1987; Glenner, 1999; Høeg et al., 2004). Cirripedes have become favored organisms for the study of marine larval settlement because of their range of life forms, their ubiquity as biofoulers, and the structural diversity of juveniles formed by metamorphosis of the settled cyprid. At the light microscopical level, the morphology of the cyprid appears to be surprisingly similar throughout the entire taxon, but studies with the scanning electron microscope have shown significant variation in the structure of the antennules (Glenner et al., 1989; Moyse et al., 1995). This is hardly surprising because it is by means of these specialized appendages that the
cyprid first explores the substratum by bipedal walking and finally attaches by irreversible cementation (Walker and Yule, 1987; Lagersson and Hoeg, 2002; Maruzzo et al., 2011). To accomplish this critical task, the four-segmented antennules are equipped with an array of sensory organs and glands. The penultimate third segment is short and carries the so-called attachment disk (AD), which is a flat surface covered with cuticular villi onto which the glands terminate that are used in both temporary adhesion and final cementation. Almost all setae are also located either on this segment or on the small fourth segment, which projects from the side of the third segment and thus extends the area from which stimuli can be picked up; and they have all been shown to be sensilla (sensory setae) (Nott, 1969; Walker et al., 1987; Lagersson and Hoeg, 2002; Maruzzo et al., 2011).

This introduces the question of whether structural diversity of the cypris antennule is correlated with the diversity of habitats and substrata used in settlement by cirripede species. With this aim, Al-Yahya et al. (2016) performed a morphometric analysis of the third segment (the attachment organ) in cyprids from a selection of barnacles inhabiting many different habitats. Significant variation was found among the investigated species, with respect to both the general shape of the segment and the structural details of the AD. Al-Yahya et al. (2016) suggested that the variation was related to the different substrata used by the species, but their analysis, based on very few structural parameters, could not adequately demonstrate this claim. Furthermore, the Al-Yahya et al. (2016) study was confined to the shape of the third segment and the structure of the AD, but it left unexamined the fourth segment, which contains a multitude of sensilla that play a key role in locating the settlement site (Walker et al., 1987; Glenner et al., 1989; Clare and Nott, 1994; Glenner, 1999; Blomsterberg et al., 2004; Kolbasov and Hoeg, 2007; Bielecki et al., 2009).

Within cirripedes, species of acorn barnacles (Thoracica: Balanomorpha) inhabiting rocky shores are an ecologically very important group that often completely dominate their habitats and subject them to analysis by multivariate statistics. For comparison, we also include one balananoidean species from an entirely different habitat, namely, epibiotic in marine sponges, and a species from the Verrucomorpha, which is the sister group to the Balanomorpha.

Materials and Methods

Larval culture and SEM preparation

We cultured larvae of 9 cypride species to the cypris stage: Megabalanus rosa Pilsbry, 1916 (n = 6), Austrominimus (=Elminius) modestus (Darwin, 1854) (n = 6), Semibalanus balanoides (Linnaeus, 1767) (n = 6), Balanus crenatus Bruguière, 1789 (n = 11), Perforatus (Balanus) perforatus (Bruguière, 1789) (n = 5), Hesperibalanus fallax (Brock, 1927) (n = 9), Balanus balanus (Linnaeus, 1758) (n = 7), Balanus spongicola Brown, 1844 (n = 4), and Verruca stroemia (O.F. Müller, 1776) (n = 7). All except the last two inhabit coastal hard-bottom communities, and all except M. rosa were collected from waters around the southern coast of England. The larvae were cultured as described in Moyse et al. (1995) and H. Al-Yahya (University of Swansea, unpubl. data). The preparation for scanning electron microscopy followed Moyse et al. (1995) and Al-Yahya et al. (2016). The SEM micrographs used for morphometric measurements were taken with either a JEOL-850 SEM or a JEOL-6335 SEM (Tokyo).

Choice of parameters

We were inspired by the approach of Al-Yahya et al. (2016) but extended our analysis to include many more features, including antennular segments 2–4 and their setae. Only the first segment was excluded from the analysis, because it carries no setae and was generally obscured from view in the SEM. The second antennular segment (as2) has an elongated shape. The short third segment (as3) carries the villus-covered AD; it forms the functional distal end of the appendage, because the short and semicylindrical fourth segment (as4) extends from it laterally (Fig. 1). Almost all antennular setae are located on the third and fourth segments; these setae
have all been demonstrated to have sensory properties and are, therefore, sensilla (Nott and Foster, 1969; Walker et al., 1987; Clare and Nott, 1994; Lagersson et al., 2003; Høeg et al., 2004; Maruzzo et al., 2011). Nevertheless, we henceforth use the neutral term “seta” in order to conform to the existing terminology for antennular features set by Bielecki et al. (2009).

**Scanning electron microscope procedure**

During observation, the stubs were rotated and tilted to bring the cypris antennules into precise orientation for measurements as explained below. We attempted to record all parameters from both antennules in any individual cyprid, but this was not always possible. In a few larvae we had to use suboptimal viewing angles for recording some parameters, and this could explain some or all of the outlying points in our multivariate analysis.

**Segment shapes**

Most measurements on as2 and as3 were recorded with the antennule observed in a perfect lateral or medial view. For AD measurements, we used perfect face-on views. In both live and preserved specimens, as4 can project at a range of angles from as3; hence, we oriented the specimens to observe this segment in a perfect lateral view.
Measurements of setae

All setae classified by Bielecki et al. (2009) were found in all species, except for a single one in *Verruca stroemia*. Most setae have a simple and slender shape, so length was the only critical parameter to record (except for terminal seta D [TS-D]). Since setae could be characteristically curved, we recorded their true length (Figs. 1–3), but we refrained from estimating curvatures because some setae are known to be very flexible in live cyprids (Maruzzo et al., 2011) and their shape is also heavily influenced when undergoing preparation for scanning electron microscopy. For length measurements, we positioned the specimen so that the particular seta had its greatest extension over the screen. Measurements were carried out from stored micrograph files based on the scale and magnification given on images. A few setae deviated from a simple shape. The TS-D on the fourth segment was an elongated sac with a characteristic surface ornamentation of cuticular reinforcement ribs (Figs. 2D, 3D). The ornamentation pattern can vary interspecifically and can also shift abruptly along the length of the seta, but we did not attempt to quantify this issue (Fig. 3D). Terminal setae A and B (TS-A + B) were measured separately but turned out to be mutually similar in all species. They were always fitted with numerous side branches (ribbon-like setules) forming a plumose seta (Fig. 3C, D). It would have been desirable to record both the length and the separation distance of these setules, but they almost always became twisted in SEM preparations and were therefore not practically measurable. The setae on the AD were hard to measure accurately. Their basal part was obscured to various degrees by either the carpet of cuticular villi or the velum or skirt surrounding the disk; entire such disk setae could be totally obscured from view in some specimens (Bielecki et al., 2009). Therefore, we omitted measurements of the postaxial disk seta, the axial disk seta, and all radial disk setae (RDS) except the medially placed RDS-5, which in most species was easy to measure because of its greater length (Fig. 3A). The tiny terminal seta C was always present but not measured.

Attachment disk features

In Figure 2E, the AD on as3 is covered by a carpet of minute cuticular villi, which can vary in density, length, and thickness (Nott, 1969; Moyse et al., 1995; Aldred et al., 2013), but Alya et al. (2016) found problems in attempting to quantify these parameters. In our micrographs, the AD is often prone to bulging parts, making it difficult to observe and count the min-
ute villi in a way suitable for statistical analysis, so this is omitted from our analysis. We recorded whether the disk is surrounded by a velum or a skirt (Al-Yahya et al., 2016), but as presence or absence only, so this information forms no part of the multivariate analysis. A typical velum (Fig. 2B) is a sheet formed by a series of long but narrow cuticular filaments that are attached on the side of the segment some distance from the perimeter of the disk. In contrast, a true skirt (Fig. 3B) is attached at the very perimeter of the disk and consists of a series of low but broad cuticular filaps (Moyse et al., 1995; Al-Yahya et al., 2016; Figs. 2, 3). A quantification in terms of attachment position, numbers, length, and width of these filaments and filaps would have been desirable, but this was also impractical because they easily become distorted in preparation for the SEM.

Parameters measured

The 26 antennular parameters recorded are illustrated schematically in Figure 1 (see Table S1, available online, for raw data of measurement). Figures 2 and 3 illustrate how the parameters were estimated on actual SEM micrographs and also serve to highlight some differences between the currently studied species. Note that the distal width of as2 as seen in lateral or medial view is always similar to the proximal width of as3; hence, we recorded only the first as parameter 4. Similarly, the distal width of as3 in lateral or medial view equates with that of the long axis of the AD seen face-on, and, accordingly, only the latter was recorded as parameter 9. In the multivariate analysis, we used the ratio of parameters 6 to 7 instead of their individual values because this ratio can be directly affected by the shape of as3.

Multivariate analysis

To compare variations in cyprid antennular morphology, a total of 25 quantitative parameters in the third and fourth segments were selected for analysis (note that characters 6 and 7 were used as a ratio in the analysis, so in total 25 characters, instead of 26, were used in the multivariate analysis; see details in Fig. 1). To remove variation due to the interspecific differences of size, all length measurements were divided by the mean length of cyprids (for the number of samples used for multivariate analysis, see Larval culture and SEM preparation, above). Variations in the parameter in antennules among species were analyzed using multivariate analysis (PRIMER 6,
Plymouth Routines in Multivariate Analysis; Clarke, 1993). Data were square-root transformed prior to analysis, and Euclidean distance was used for similarity matrix calculation. Nonmetric multidimensional scaling (nMDS) was conducted to generate the two-dimensional plots of the antennular parameters between barnacle species. Analysis of similarity (ANOSIM) was conducted to test for differences in antennular parameters between species. Under ANOSIM, the degree of similarity between pairs can be indicated by R-values in the Global test, in which R ranged from 0 to 1, where 0 indicates high similarity and 1 indicates low similarity. Chan et al. (2007a, b) have demonstrated the utility of this multivariate technique to discriminate the scutum and tergum parameters among barnacle species. Similarity percentage (SIMPER) analysis was conducted to examine the parameters that contributed to the differences among species (see Chan et al., 2007b).

Results

Scanning electron microscopy analysis

The SEM micrographs showed that the antennular structure was surprisingly similar in almost all of the investigated species. Most significantly, mere inspection of the SEM photos revealed no obvious differences in the structure of setae, neither among the hard-bottom balanomorphans nor between these and the two remaining species. All of the setae found and classified by Bielecki et al. (2009) in Megabalanus rosa were present in the nine species and with virtually the same relative positions and morphologies. This is also true for the setae on the AD that were excluded from the multivariate analysis. The only exception was Verruca stroemia, where the RDS-5 is not exceptionally longer than the other RDS. We particularly emphasize that all species have exactly the same setation on the fourth segment, which extends laterally from the third segment and during settlement performs a sweeping motion that increases the substrate area probed by the exploring cyprid (Clare and Nott, 1994; Maruzzo et al., 2011).

The most striking difference between the species concerned was the shape and structure of the third antennular segment: the attachment organ. In both Balanus spongicola and V. stroemia, the shape of the third segment is somewhat shoe shaped in lateral view, with the dorsal (preaxial) side of the segment longer than the ventral (postaxial) side. The result of this is a ventrally angled AD with an elongated oval outline when viewed face-on. All of the hard-bottom balanomorphans had a third segment that was almost symmetrically bell shaped and a distally facing AD with a near-circular outline.

Statistical analysis

The impression from the SEM micrographs was confirmed by the multivariate analysis of the structures measured, because the species fell into two clearly separated clusters. ANOSIM showed significant differences for the species included in the analysis ($P < 0.05, R = 0.43$). Cluster A was composed of V. stroemia and the sponge-associated B. spongicola; ANOSIM indicated no significant differences between them (Table A1). Cluster B included all the balanomorphans from hard substrata in the coastal zone (Fig. 4). Most of the species within cluster B had no significant differences in antennule parameters (Table A1). However, a pairwise comparison of the R-values between cluster A and cluster B revealed that about half ranged from 0.9 to 1.0. Pairwise comparisons of species pairs within cluster B ranged from 0.3 to 0.7 (Table A1). SIMPER analysis showed that two parameters, the ratio between the dorsal and ventral length of as3 and the angle subtended between the dorsal side and the attachment disk, are the key parameters that contribute >40% of the differences between cluster A and cluster B. Within cluster B, the angle between the dorsal side of as3 and the plane of the AD is the key parameter, contributing >20% of the differences in significant species pairs (Table A1).

Velum and skirt

Our SEM photos indicated that velum and skirt are not nearly as distinct from each other as was stated by Al-Yahya et al. (2016). A typical velum with numerous thin filaments (Fig. 2B, C) was found in Semibalanus balanoides, while a typical skirt consisting of broad flaps was found in B. spongicola and V. stroemia (Fig. 3B). But some species had structures circum-scribing the AD that were intermediate between these two extremes. Balanus balanoides (Fig. 3A) had filaments or flaps that were rather few in number, almost square in shape, and attached closer to the disk perimeter than in, for example, S. balanoides. Thus, typical vela and skirts sensu Al-Yahya et al. (2016) may be extreme versions of the same general structure.

Discussion

In our multivariate analysis of cypris antennular morphology, all balanoidae species from coastal hard-bottom communities formed a single cluster, clearly separated from a cluster formed by the balanoidean Balanus spongicola and the non-balanomorph Verruca stroemia. These two species inhabit entirely different substrata. Balanus spongicola is normally epibiotic in marine sponges, although occasionally found on physical substrata, while V. stroemia inhabits deeper waters and is normally epibiotic, although found on a wide variety of organisms (Southward and Crisp, 1963; Southward, 2008).

Inspection of the SEM micrographs showed that the antennular setation is almost identical in number and structure in all species examined, so it is likely that the separation between the hard-bottom forms (cluster B) and B. spongicola and V. stroemia (cluster A) is primarily due to parameters 1–10, concerning the shape of the segments. Both V. stroemia and B. spongicola have a third segment that is shoe shaped, while the hard-bottom forms have a symmetrically bell-shaped segment, a difference also found among the species studied by...
Moyse et al. (1995) and Chen et al. (2013). In their study comprising species from a wide range of taxa and habitats, Al-Yahya et al. (2016) suggested that a shoe-shaped third segment surrounded by a skirt is associated with an epibiotic habitat, while a bell-shaped segment surrounded by a velum is associated with a hard-bottom habitat; but their statistical analysis failed to adequately support this claim. It is nevertheless striking that a bell-shaped third segment has only been found in cyprids from hard-bottom balanomorphans and in the very few pedunculated barnacles from this same habitat, namely, 

\textit{Pollicipes pollicipes} and \textit{Capitulum mitella} (Moyse et al., 1995; Rao and Lin, 2014; Al-Yahya et al., 2016). This suggests that this segment shape is indeed associated with hard bottoms; but a detailed morphometric analysis, as in the present paper, that also includes \textit{P. pollicipes}, \textit{C. mitella}, and some of the numerous hard-bottom-inhabiting species from the balanomorph superfamilies Chthamaloidea and Corunuloidea, is needed to further substantiate this claim. The relation between a velum and hard-bottom habitats is more dubious, because we found velum and skirt not to be very clearly separated in structure. Yet it is again striking that species from very high-energy, rocky intertidal habitats (\textit{C. mitella}, \textit{P. pollicipes}, \textit{Semibalanus balanoides}, and species of \textit{Chthamalus} and \textit{Tetraclita}) always seem to have not only a bell-shaped as3 but also a typical velum consisting of numerous long and thin filaments (Moyse et al., 1995; Chan, 2003; Al-Yahya et al., 2016; this study and our unpublished SEM data). In contrast, both \textit{B. spongicola} and \textit{V. stroemia} have a typical skirt consisting of broad and low cuticular flanges. Here we wish to emphasize that little variation was found in the antennular structure among cyprids of balanomorph species from coastal hard-bottom habitats. These species are also potentially fouling barnacles, and while we did not include the model species \textit{Amphibalanus (=Balanus) amphitrite} in the present analysis, the detailed description in Glenner and Høeg (1995) shows that its antennular structure is exactly as in the other hard-bottom species studied here.

In conclusion, our analysis and previous studies show that there is significant variation in cypris antennular structure among cirripedes. This includes both the specific array of setae and the shape and detailed structure of the attachment organ, but the extent to which this structural variation is correlated with differences in habitat and settlement remains somewhat uncertain (Glenner et al., 1989; Glenner and Høeg, 1995; Moyse et al., 1995; Blomsterberg et al., 2004, Kolbasov and Høeg, 2007; Brickner and Høeg, 2010; Chen et al., 2013; Rao and Lin, 2014; Al-Yahya et al., 2016). Nevertheless, the present analysis and the results in Al-Yahya et al. (2016) clearly show that species from coastal hard-bottom habitats have a unique and almost identical antennular structure. This agrees with Di Fino et al. (2014), one of the very few comparative studies of settlement biology in balanomorphans, which, contrary to some earlier claims, found no difference in the reaction to settlement cues between \textit{Amphibalanus (Balanus) improvisus} and

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Nonmetric multidimensional scaling plot of 25 parameters (note that characters 6 and 7 were used as a ratio in the analysis) measured from antennular morphology in cyprids of \textit{Verruca stroemia} and 8 species of balanomorph barnacles. Cluster A contains \textit{V. stroemia} and \textit{Balanus spongicola}. Cluster B contains all the remaining balanomorph species, all from hard-bottom habitats.}
\end{figure}
A. amphitrite. In the absence of structural differences between cyprids, studies on settlement in hard-bottom-inhabiting barnomorphans, which are also highly important as marine foulers, should continue to focus on refined experimental approaches (Aldred and Clare, 2008, 2009). One difficult but very promising avenue might well be electrophysiological experiments with cypris models that could lead to insight into the relation between sensory input and the resulting behavioral response (Harrison and Sandeman, 1999).

Acknowledgments

The authors wish to dedicate this paper to our friend Dr. Graham Walker, formerly at the Marine Science Laboratories Menai Bridge, and to our recently departed colleague, Dr. John Moyse, formerly at the University of Swansea, who understood the intimate relation between the structure and biology of cirripede larvae. The study was financed by grants to JTH from the Carlsberg Foundation, the Danish Agency of cirripede larvae. The study was understood the intimate relation between the structure and biology of cirripede larvae. The study was financed by grants to JTH from the Carlsberg Foundation, the Danish Agency of Cirripedia: Thoracica). II. Larval morphology and development. J. Mar. Biol. Assoc. U.K. 46: 175–187.

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## Appendix

### Table A1

Pairwise comparison analysis in analysis of similarity and R-statistics for antennular features in cyprids from the nine investigated species of cirripedes

| Species pairwise comparison                      | P-value | R-statistics |
|--------------------------------------------------|---------|--------------|
| Balanus crenatus vs. Megabalanus rosa            | <0.05   | 0.33         |
| Balanus crenatus vs. Balanus balanus             | NS      | 0.09         |
| Balanus crenatus vs. Balanus perforatus          | NS      | 0.26         |
| Balanus crenatus vs. Hesperibalanus fallax       | <0.05   | 0.33         |
| Balanus crenatus vs. Balanus spongicola         | <0.05   | 0.99         |
| Balanus crenatus vs. Verruca stroemia           | <0.05   | 0.41         |
| Balanus crenatus vs. Semibalanus balanoides     | NS      | 0.08         |
| Megabalanus rosa vs. Balanus balanus            | NS      | 0.06         |
| Megabalanus rosa vs. Balanus perforatus         | NS      | 0.22         |
| Megabalanus rosa vs. Hesperibalanus fallax      | NS      | 0.01         |
| Megabalanus rosa vs. Balanus spongicola         | <0.05   | 1            |
| Megabalanus rosa vs. Verruca stroemia           | <0.05   | 0.72         |
| Megabalanus rosa vs. Austrominius modestus      | NS      | 0.14         |
| Megabalanus rosa vs. Semibalanus balanoides     | <0.05   | 0.67         |
| Balanus balanus vs. Balanus perforatus          | NS      | 0.18         |
| Balanus balanus vs. Hesperibalanus fallax       | NS      | 0.09         |
| Balanus balanus vs. Verruca stroemia            | <0.05   | 0.81         |
| Balanus balanus vs. Austrominius modestus       | <0.05   | 0.19         |
| Balanus balanus vs. Semibalanus balanoides      | <0.05   | 0.36         |
| Balanus balanus vs. Balanus spongicola         | <0.05   | 1            |
| Balanus perforatus vs. Verruca stroemia         | <0.05   | 0.64         |
| Balanus perforatus vs. Austrominius modestus    | <0.05   | 0.34         |
| Balanus perforatus vs. Semibalanus balanoides  | <0.05   | 0.48         |
| Balanus perforatus vs. Balanus spongicola      | <0.05   | 0.75         |
| Hesperibalanus fallax vs. Balanus spongicola   | <0.05   | 0.79         |
| Hesperibalanus fallax vs. Verruca stroemia     | <0.05   | 0.66         |
| Hesperibalanus fallax vs. Austrominius modestus| NS      | 0.06         |
| Hesperibalanus fallax vs. Semibalanus balanoides| <0.05 | 0.33         |
| Balanus spongicola vs. Verruca stroemia        | NS      | 0.066        |
| Balanus spongicola vs. Austrominius modestus   | <0.05   | 1            |
| Balanus spongicola vs. Semibalanus balanoides  | <0.05   | 0.59         |
| Austrominius modestus vs. Semibalanus balanoides| <0.05 | 0.2          |

NS, not significant.