Geographic distribution of a gall-inducing copepod *Allopodion ryukyuensis* on *Montipora* corals along Ryukyu Archipelago, Japan, and Green Island, Taiwan

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**Abstract** *Allopodion ryukyuensis* is a gall-inducing copepod of *Montipora* coral that has been collected from the coral reefs of Sesoko Island, Okinawa, Japan. The current study was conducted to elucidate its geographic distribution along the Ryukyu Archipelago from Yonaguni Island to Amami Island, including Green Island, Taiwan. The result shows that *A. ryukyuensis* was found from *Montipora* collected from all study sites.

**Keywords** Gall-inducing copepod, *Allopodion ryukyuensis*, Coral, Sesoko Island, Coral parasite

**Introduction**

Coral reefs are valuable ecosystem supporting structures housing numerous varied organisms on the surface or inside the coral tissues, as well as on the calcium carbonate skeleton. Coral-associates are significantly diverse from bacteria to vertebrates, and they can use the corals for food or shelter. Crustaceans such as crabs, shrimps, and tiny copepods are known to be associated with corals; however, it is likely that many copepods exist in these regions that are unknown and unidentified (Humes 1985; Cheng et al. 2016). Cheng et al. (2016) reported that 66 genera of scleractinian corals serve as hosts to 363 copepod species (288 cyclopoids, 68 siphonostomatoids, and 7 harpacticoids).

Gall-inducing copepods have special relationships with host corals: they have a defense mechanism against coral nematocysts, and some of them can deform coral skeletal growth to make a rigid housing for themselves. There are six known species of gall-inducing copepods on scleractinian corals (Table 1). *Allopodion ryukyuensis* Kim and Yamashiro, 2007 was first observed in 1999 as an unknown copepod species from Sesoko Island inhabiting galls and crypt on encrusting *Montipora informis* Bernard, 1897; the estimated diameter of the galls was 1.56±0.16 (mean±SD, n=54) and the number of eggs per gall were 5.6±3.2 (n=40) (Yamashiro and Iha

**Table 1** A list of gall-forming copepods on scleractinian corals.

| copepod          | host coral          | locality            | reference                  |
|------------------|---------------------|---------------------|----------------------------|
| Isomolgus desmotes Dojiri, 1988 | Seriatopora hystrix   | Indonesia          | Dojiri 1988                |
| Pinomolgus gallicolus Dojiri & Grygier, 1990 | Echinopora lamellosa | Lizard Island, Australia | Dojiri and Grygier 1990    |
| Haplomolgus montiporae Humes & Ho, 1968 | Montipora aequituberculata | Taiwan            | Cheng et al. 2010          |
| Spaniomolgus sp. | Stylophora pistillata | Saudi Arabian Red Sea | Ivanenko et al. 2014       |
| Allopodion ryukyuensis | Montipora sp.       | Sesoko Island, Japan | Kim and Yamashiro 2007     |
| Xenomolgus varius Humes & Stock, 1973 | Porites sp.         | Sesoko Island, Japan | Kim and Yamashiro 2007     |
This cyclopoida copepod was then described as a new species (Kim and Yamashiro 2007).

Although *A. ryukyuensis* is abundant in encrusting *Montipora* corals around Sesoko Island (Yamashiro and Iha 2004; Kim and Yamashiro 2007), their geographic pattern in the coral reefs has not been determined along the Ryukyu Archipelago. Recently, Cheng et al. (2010) were the first to report *A. ryukyuensis* from *Montipora aequituberculata* Bernard, 1897 at Wanlitong in southern Taiwan.

**Materials and methods**

Galls of *A. ryukyuensis* were determined at 1–5 m depths in coral reefs along the Ryukyu Archipelago from Yonaguni Island to Amami-Oshima Island, and in Green Island, Taiwan. Nineteen islands including 37 sites were surveyed. The survey time was generally 30 min or more at each site, during which time photographs were taken and information about the host coral such as colony shape was recorded. Fig. 1A–C shows the galls induced by the copepod *A. ryukyuensis*. Both gall size (about 1.5 mm in diameter) and shape were conspicuous and specific structure of *A. ryukyuensis*, making these galls easy to find and identify in the field. At present there were no other gall-forming copepod on encrusting *Montipora*. The survey of copepods began in 1999, when this particular copepod was observed for the first time in Sesoko Island, and continued on an occasional basis until 2020. As necessary, 2 to 3 coral specimens for each island were collected to observe the copepod, obtained by picking and breaking the galls, under a dissecting microscope (SMZ-1000, Nikon Co.) or under a digital microscope (VHX 1000, Keyence Co.).

**Results and discussion**

Fig. 1D shows one female five eggs, and one male in one gall. Fig. 2 shows the distributional records of *A. ryukyuensis*; 19 islands in the Ryukyu Archipelago, and

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**Fig. 1** A. Gall-inducing copepod *A. ryukyuensis* on/in the encrusting coral *Montipora informis* (Okinawa Is.). B. Dried skeleton showing numerous galls (arrows) formed by the copepods. C. Gall with an opening at the top. Coral polyps and coenosteum papillae (white elaborations) are shown. D. Male (left), female, and eggs (initial number: 6), collected on January 13, 2021, in Sesoko Is.
Green Island in Taiwan were surveyed. Depending on the distance and map size, several locations were expressed as a single dot in Fig. 2. *A. ryukyuensis* was observed in most sites, except where no host corals (mainly encrusting *Montipora* species) were present. In shallow coral reefs in the Ryukyus, branching corals such as *Montipora digitata* (Dana, 1846) and *Montipora samarensis* Nemenzo, 1967 formed large aggregates; however, galls formed by *A. ryukyuensis* were found only on encrusting *Montipora* species, with the exception of specimens at Kurima Island, off Miyako Island associated to branching *Montipora* sp. was determined as a host (no sample collected). In Green Island, *A. ryukyuensis* was established on the foliose *M. aequituberculata* in a reef on the east coast of Green Island, but *M. informis* was the host coral in the other four reefs in the island.

The present results showed that *A. ryukyuensis* was found in a wide range from Taiwan to the Amami islands, Japan. Taiwan is located in a tropical sea, and the Amami islands are located at much higher latitudes (28°–29° N). Further studies are required to determine the geographic distribution of the copepod extending to the south, such as in the Philippines and Indonesia, and to the north, in such areas as the Yakushima and Tanegashima Islands, and even further north since zooxanthellate corals without forming reef structure are distributed around the Boso Peninsula, Japan (Veron 1992; Yamano et al. 2011).

*A. ryukyuensis* was exclusively found on *Montipora*, particularly encrusting ones, which are distributed widely in coral reef areas and non-reef areas in temperate

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**Fig. 2** Maps showing the geographical distribution of the gall-inducing copepod *Allopodion ryukyuensis*. Black circles indicate the sites where galls of *A. ryukyuensis* were observed.
regions of Japan (Veron 1992; Nishihira and Veron 1995). Cheng and Dai (2010) reported *A. ryukyuensis* from *M. aequituberculata* at Wanlitong in southern Taiwan, whereas in the present survey (2019) it was also found on the same host in Green Island, Taiwan.

Family Acroporidae contains seven genera, two of which, *Acropora* and *Montipora* have numerous species, most acting as the dominant corals in reefs. *A. ryukyuensis* selects *Montipora* as its only host genus. This host specificity suggests a co-evolution, as has been observed in other copepod-coral associations (Chan et al. 2020).

These results showed that *A. ryukyuensis* was found in most coral reefs over approximately 1,400 km along the Ryukyu Archipelago from Taiwan to the Amami islands (Fig. 2). Nevertheless, *A. ryukyuensis* was not discovered until 1999 and has only been described recently (Kim and Yamashiro 2007). Copepods have been highly successful in association with many marine invertebrates (Humes 1985), and the true diversity of coral-associated copepods is underestimated (Chan et al. 2020). In contrast, coral-associated copepods are scarce in the eastern Pacific Ocean and the Caribbean Sea, spreading eastward from the Indo-West Pacific (Chan et al. 2020). *A. ryukyuensis* can be expected to disperse by releasing larvae which will find suitable hosts and develop rigid gall houses on them.

The relationship between host coral and gall-inducing copepods is not clear in terms of whether it is symbiotic or parasitic (Barton et al. 2020). An excess of galls covering the coral tissue appeared to decrease coral activities (Fig. 1B), although inhabiting copepods also excreted nutrients such as ammonium to the host. A recent study showed another aspect of coral-copepod association: gall-inducing copepods changing microbial communities of gall coral tissue (Shelyakin et al. 2018). Further studies are needed to determine the impact of coral-associated copepods on coral health in a changing environment, such as temperature fluctuations or increasing infectious diseases.

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**Compliance**

Coral sampling was done with the approval of Okinawa Prefecture, Japan.

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