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An Anatomical Description of a Miniaturized Acorn Worm (Hemichordata, Enteropneusta) with Asexual Reproduction by Paratomy

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Abstract

The interstitial environment of marine sandy bottoms is a nutrient-rich, sheltered habitat whilst at the same time also often a turbulent, space-limited, and ecologically challenging environment dominated by meiofauna. The interstitial fauna is one of the most diverse on earth and accommodates miniaturized representatives from many macrofaunal groups as well as several exclusively meiofaunal phyla. The colonization process of this environment, with the restrictions imposed by limited space and low Reynolds numbers, has selected for great morphological and behavioral changes as well as new life history strategies. Here we describe a new enteropneust species inhabiting the interstices among sand grains in shallow tropical waters of the West Atlantic. With a maximum body length of 0.6 mm, it is the first microscopic adult enteropneust known, a group otherwise ranging from 2 cm to 250 cm in adult size. Asexual reproduction by paratomy has been observed in this new species, a reproductive mode not previously reported among enteropneusts. Morphologically, Meioglossus psammophilus gen. et sp. nov. shows closest resemblance to an early juvenile stage of the acorn worm family Harrimaniidae, a result congruent with its phylogenetic placement based on molecular data. Its position, clearly nestled within the larger macrofauna hemichordates, suggests that this represents an extreme case of miniaturization. The evolutionary pathway to this simple or juvenile appearance, as chiefly demonstrated by its small size, dense ciliation, and single pair of gill pores, may be explained by progenesis. The finding of M. psammophilus gen. et sp. nov. underscores the notion that meiofauna may constitute a rich source of undiscovered metazoan diversity, possibly disguised as juveniles of other species.

Introduction

Hemichordata is a phylum of exclusively marine deuterostomes traditionally divided into the classes Pterobranchia and Enteropneusta [1–4], the latter including Psychoderidae, Spongeliidae, Harrimaniidae and Torquaratoridae e.g., [4,5]. However, Enteropneusta is in several recent studies [6,7], though not all [8], considered parphyletic with respect to the Pterobranchia. Whereas all known acorn worms are solitary and range from 2–250 cm in adult size, constituting part of the benthic macrofauna, the sessile pterobranchs are colonial and consist of multiple minute zooids, each usually 0.5–5 mm long [9–11]. The origin of this deviant and small body plan is still poorly understood, especially if they nest among clades of macroscopic solitary acorn worms [6,7]. It is thus inferred that a pterobranch ancestor shared traits with these and may have shown resemblance to a solitary, mobile acorn worm [6,7].

The meiofauna comprises free-living animals that can pass a 1 mm (0.5 mm) sieve but are retained on a 31 μm (44 μm) sieve [12,13]. Metazoan meiofauna is dominated by protostomes, including miniaturized representatives of Annelida, Arthropoda, and Mollusca, as well as a variety of mostly meiofaunal lineages such as Gastrotricha, Kinorhyncha, many Platyhelminthes groups, Rotifera and Tardigrada [12]. Deuterostomia, the other major bilaterian clade, consists of three major extant lineages—Echinodermata, Hemichordata, Chordata and arguably Acoelomorpha (including Xenoturbellida) [14–21]. Most deuterostome species are macrofaunal, while microscopic, meiofaunal representatives of the deuterostome lineages are restricted to a handful of Tunicata (Chordata), Holothuroidea (Echinodermata), and, if truly deuterostome, most acoelomorphs [22–30]. Most remarkable is the phylogenetic diversity and disparity in body plans found in this size category, wherefrom three of the most recent phyla Gnathostomulida, Loricifera, and Micrognatho-
zoa were described [31–33]. This fraction of small-sized metazoans is extraordinarily numerous and diverse in the interstices among sand grains, an environment that includes representatives of more than twenty of the thirty–some animal phyla [12–13]. This hidden and often overlooked source of diversity was highlighted in recent meiofaunal surveys from two of the best-studied shallow water localities in the North Sea and the Mediterranean, with up to 37% of the reported species being undescribed [36,37]. The use of genetic tools has also aided to identify cryptic species in this environment [38–41], amplifying the magnitude of unknown meiofaunal biodiversity. However, to date no adult acorn worm had been reported from the interstitial environment.

Meiofaunal animals may have been major players in the earliest stages of the diversification of bilaterian life [13,42]. Many others became miniaturized secondarily from macrofaunal ancestors [43–46]. The most popular evolutionary hypotheses explaining the many miniaturized forms in the interstitial environment, including meiofaunal ascidians and holothurians, is progenesis [26,29,47], based mainly on their resemblance to larval or juvenile stages of their macrofaunal relatives. A second argument in favor of progenesis has to do with the difficulties in adapting to the interstitial environment, requiring one macroevolutionary change rather than a gradual decrease in size [43,47]. With an inherent early offset of somatic growth in a young life stage facilitated by, e.g., early or fast maturation, a one-step evolutionary pathway is accessed (progenesis); leading to the permanent colonization of the interstitial habitat. Paedomorphism (mainly progenesis rather than neoteny) is therefore suggested to be the most likely evolutionary pathway for the origin of many interstitial taxa, especially those with extant macrofaunal relatives [43,45,47–52]. This is possible since many macrofaunal species, including enteropneusts [53,54], already spend part of their life cycle in the interstitial environment as newly settled larvae and juveniles growing up in this protected habitat [12,13].

Hemichordata present a variety of reproductive modes including different forms of asexual reproduction [55–57], which, though possibly homologous, may add to the complexity of tracing their evolutionary history and address theories such as progenesis. The most common form of asexual reproduction in Enteropneusta is architomy (fission/fragmentation followed by regeneration of individuals). This is described as a transverse fission leading to a posterior (hepatic) regenerating individual and an anterior (branchio-genital) individual [55]. The posterior genital part of the anterior branchio-genital individual fragments into several ‘regenerate’ zooids that regenerate into new individuals post fission [58,59]. Paratomy is an alternative to architomy and common in, e.g., Annelida and Acoela [60–62]. It is described as transverse fission following a complete regeneration of organ systems in individuals developing in alignment with the anterior-posterior body axis, head to tail fashion [62]. Budding is common in the colonial Pterobranchia (Hemichordata) and can in, e.g., Cephalodiscus, be regarded as a special form of ‘paratomy’ where the axis of the new zooid does not correspond to the axis of the old zooid, yet may detach [55,63]. In Rhabdobalanus the bud may develop along the anteroposterior axis to full maturity [55,57], however a bud has never been observed detaching from the mother zooid.

Here we report the first meiofaunal, interstitial adult acorn worm and provide a detailed description of its anatomy and possible reproduction mode. We further test its phylogenetic position using DNA sequence data and standard phylogenetic analyses. Possible evolutionary scenarios for this, the smallest acorn worm known to date, are discussed.

Results

Taxonomic treatment

Phylum Hemichordata Bateson, 1885
Class Enteropneusta Gegenbaur, 1870
Family Harrimaniidae Spengel, 1901
Genus Meioglossus gen. nov.

Diagnosis. Intestinal, microscopic enteropneust with slender, completely ciliated body. Proboscis elongated; with a pair of dorso-lateral proboscis pores at the base; indistinct neck. Longitudinal blood vessel running underneath the collar cord and projecting into the protocoel, to enlarge into glomerulus. Pericardium small; attached postero-dorsally to the wall of the protocoel and ventrally to the glomerulus; indistinct heart sinus. Stomochord and mucus skeleton absent. Collar region more than half the length of proboscis; with paired mesocoels separated by longitudinal septa; mesocoelic pores absent. Perihaemal cavities present, terminating at base of proboscis. Peribuccal cavities absent. Trunk region with one pair of anterior dorso-lateral Gill pores. Mesoocoels and metacoels separated by a transverse septum, anterior to the Gill pores, at the level of the posterior collar ridge.

Etymology. From Greek, micro, smaller and glossa, tongue, indicating the size of this species (meio- is typically used in enteropneust genera, such as Glossobalanus, Balanoglossus).

Meioglossus psammophilus sp. nov.

Glossobalanus crozieri van der Horst, 1924 (juvenile): Tyler 2001 [64]; 3–12 (Figure 1).

Diagnosis. Body hyaline with yellow gut. Proboscis delineated posteriorly by a circumferential ring of cilia. Protocoel extending most of the length and width of the proboscis; lined by a one-fiber thick ring of longitudinal muscles, encircled by circular musculature. Collar with middle circumferential groove lined by a ring of long cilia and epidermal glands. Dorsal collar cord running subependially, neuropores absent. Anterior trunk with slight longitudinal depression mid-dorsally; one pair of anterior dorso-lateral Gill pores lacking the characteristic ciliation of the distal part of the Gill pores. Posterior trunk with supratrumenal anus and large terminal glands. Sexual reproduction likely; with sperm in paired testes or free in metacoel. Asexual reproduction by transverse fission, in the form of paratomy.

Etymology. From Greek, psamm-, sand, and philos, friend, referring to the interstitial life habit of the adults of this species.


Paratypes. Forty-one specimens (males only) from coral sand at reef, 15 m depth, Carrie Bow Cay, Belize (16°48.2’N, 88°04.6’W), April 2009 and January 2010, leg. K. Worsaae (ZMUC-ENP-2 to ZMUC-ENP-42). Forty-one specimens (no sexually mature) from coral sand at reef, 2–12 m depth, Windsor Beach and Harrington sound, Bermuda (32°19.9’N, 64°40.6’W; 32°19.95’N, 64°43.69’W), October 2007, leg. K. Worsaae & W. Sterrer (ZMUC-ENP-43 to ZMUC-ENP-43); none of these with sperm whereas a previous June 2005 collecting in Bermuda yielded several males (not preserved). All material deposited at the Natural History Museum, Denmark (SNM) (30 specimens as permanent whole mounts, 16 on SEM stubs, 8 sectioned on slides or grids, 9 embedded in resin, as well as 10 vials with ethanol-fixed specimens, 9 vials with ethoh-fixed specimens; see Table 1 for details). Additional animals were photographed and recorded alive, and due to squeezing discarded afterwards or fixed for DNA extraction. Roughly one third of the examined species exhibited
paratomy. DNA sequence data were obtained from one entire specimen from Windsor Beach, Bermuda.

Description

Measurements on holotype; ranges in parenthesis including paratypes and live recordings (see Table 1).

Body slender, contractile, 611 μm long (260–611 μm). Proboscis 170 μm long (92–178 μm) and 89 μm wide (50–91 μm), 1/3 the length of animal when stretched; no mid-dorsal groove; collar 115 μm long (62–150 μm) and 115 μm wide (56–115 μm), trunk 326 μm long (130–326 μm) and 115 μm wide (56–115 μm) (Figures 1A, C–G, 2). Proboscis neck indistinctive; only a shallow constriction between proboscis and collar region. Instead, posterior and lateral areas of proboscis epidermis are connected directly to collar epidermis; ventral mouth opening area restricted (Figures 1A, B, D, 2). Neck supporting structures such as stomochord and nuchal skeleton not present (Figure 3B, C).

Epidermis composed of single layer of mucus-secreting, multiciliated cells, with two circumferential ciliary bands. Anterior band lining posterior proboscis border (pre-oral ciliary organ) and...
Table 1. Type material and no. of specimens examined with different methods in the presented study.

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terminating in v-shape ventrally in front of the mouth opening (Figure 1A). Posterior ciliary band lining circumbuccal groove that subdivides the collar region into an anterior and posterior ridge (Figures 1A, 4A, 5A, B, E, 6A, E–G). Single pair of simple gill pores, gill bars absent. Locomotion slow, primarily ciliary though guided by the muscular proboscis and by a reversal in ciliary beat, equally efficient in anterior as well as posterior direction (see online movies of live animals). Hepatic sacculation and gonadal wings lacking (Figure 1A–G).
Proboscis with protocoel as narrow, unpaired, central lumen extending three quarters the length (Figures 1A, D, 2) and with paired posterior dorso-lateral proboscis pores; pores only detected through 3D reconstruction of serial semi-thick sections (Figure 2, activate 3D model and see view B). Protocoel housing the pericardium-glomerulus complex (Figure 3C, E). Pericardium as small coelomic sac (ca. 8 mm long, 8 mm wide, 7 mm high); ventrally adjoined by voluminous glomerular vessel and postero-dorsally attached to the extracellular matrix (ECM) separating protocoel and epidermis. Glomerulus as enlarged blood plexus within ECM (about 27 μm in length, 23 μm in width and 13 μm in height), lined by protocoelic cells (podocytes, supposedly mediating ultrafiltration) (Figure 3E, H). Pericardium-glomerulus complex attached to posterior wall of protocoel only by strands of ECM, also containing longitudinal blood vessel from posterior body region (Figures 2, view C in activated 3D model; 3E); stomochord absent. Paired mesocoels present along collar region, separated dorsally and ventrally by longitudinal septa (Figure 3A), and posteriorly separated from metacoels by transverse septum, located anterior of trunk gill pores at the anterior trunk (Figure 2). Mesocoelic cavity narrow to indistinct, mesocoelic canals absent. Paired metacoels (separated by dorsal and ventral longitudinal septa) extend along entire trunk region (Figures 1B, 2); metacoels dorso-anteriorly projecting as perihemal cavities through collar region into base of the proboscis (neck absent) with anterior-most position recognized only by presence of paired dorsal longitudinal muscle bundles (Figure 5C); ventro-lateral peribuccal cavities absent. Large endodermal cells of midgut severely reduce coelomic space of trunk metacoels (Figure 1A, C, D).

Mouth opens ventrally on anterior margin of collar into short but wide buccal cavity, followed by collar and pharyngeal region of the trunk. When specimen is retracted, transverse folds protrude into the pharyngeal lumen (Figures 1A, C–D, 3A, B, 4A, 1). A single pair of indistinct dorso-lateral gill pores (best detected with
sectioning) present on anterior margin of trunk (Figures 1D, 2, 4A–B). Entire gill duct and circular gill pore lined by non-ciliated cells with cell surfaces bordered evenly by slender microvilli measuring about 2\(\mu\)m in length (Figure 4A, B). Primary and secondary gill bars absent. Pharynx followed by esophagus posterior of the gill pores within anterior trunk region (Figures 1A–D, 3A, B, 4A); esophagus delineated posteriorly by a muscular constriction before the midgut and heavily ciliated hindgut (Figures 1A, C–D, 4A, 5A, C). Dorsal supraterminal anus followed by a short postanal tail containing numerous 10 \(\mu\)m long oval glandules (8–14 \(\mu\)m) (Figure 1C). In several individuals the midgut contained diatoms (see online LM movie of live animal).

Body wall musculature composed of simple smooth inner longitudinal muscles, extending the full body length, and outer circular muscles, most developed in proboscis (locomotory organ) and lacking in posterior trunk (Figures 3C–E, 5A, C). Besides, inner circular and longitudinal muscles surrounds the intestinal system; with ‘sphincter’ muscles at esophagus-midgut (Figure 5A, C) and midgut-hindgut borders (Figure 1C, 5A); anal sphincter not detected. The proboscis body wall contains longitudinal muscles lining the protocoel with a single ring of about 40–60 muscle fibers (1–3 \(\mu\)m thick, up to 10 \(\mu\)m apart); external to these are about 30 circular muscles (1–2 \(\mu\)m thick, 3–6 \(\mu\)m apart) forming an orthogonal muscle grid together with the longitudinal muscles.
Figures 1D, 3C, D, 5A, C; see online CLSM 3D movie of proboscis. The collar contains about 20 dense circular muscles and about 10 thinner slightly oblique circular muscles only visible at the dorsal part of collar, with all 30 collar muscles lining the paired mesocoels (Figures 4I, 5A, C). Two round and ca. 10 μm long phalloidin-stained, presumably muscular structures of unknown function were detected at base of proboscis (map), where proboscis muscles meet trunk muscles, and near the points where proboscis pores connect to protocoel. The two dorsal muscle bundles of each 10 longitudinal trunk strands terminate at map (Figure 5C), both extending antero-dorsally from the trunk as perihemal diverticula (extending metacoels) into the collar. Along the trunk in posterior direction, these paired muscle bundles run first ventrally along the anterior esophagus, except for a few splitting off dorsally, and a few additional oblique running laterally (Figure 5C; see online CLSM 3D movie of trunk). Along the mid-esophagus, additional longitudinal, oblique and diagonal muscles join the two bundles; all of them fanning out along the posterior esophagus to form a dense net surrounding the trunk, only interrupted by the dorsal and ventral longitudinal septa. The net contains about 40 longitudinal muscles (1–3 μm thick, evenly distributed), continuing along the posterior trunk to insert at the posterior hindgut (Figure 5A, C). No external body wall circular muscles were found in the posterior trunk region.

The enteropneust nervous system is mainly composed of neuroepithelial nerve cells with cell bodies embedded in the epidermis and neurites forming a basiepidermal nerve plexus. In M. psammophilus gen. et sp. nov. the nerve net is most distinctive in Figure 4. Meioglossus psammophilus gen. et sp. nov., sagittal sections, transmission electron micrographs. A. Median section of collar region, showing pharyngeal lumen and esophagus. B. Close up of gill pore. C. Close up of ventral side showing middle groove and ciliary band lined by glandular cells. D. Dorsal trunk, epidermis, sperm and flagella. E. Sperm flagella (double cilia in left flagellum?). F. Close up of sperm, transverse and sagittal view. G. Flagella and sperm heads in metacoel. H. Sperm head, sagittal, median view. I. Close up from A of dorsal pharyngeal foldings and basiepidermal nerve tissue. J. Flagellae and sperm head, transverse view. Abbreviations: aa, anchoring fibre apparatus; ba, electron dense cytoplasm basally; c1, c2, double cilia of flagella; cy, cytoplasm; cb1, cb2, 1. & 2. ciliary band; ce, centriole; ci, cilium; cm, circular muscles; en, endodermal cell; ep, epidermis; es, esophagus; glc, glandular cells; gp, gill pore; hg, hindgut; im, longitudinal muscles; mec, metacoel; mg, midgut; mo, mouth opening; mv, microvillus; n, nucleus; nt, nerve tissue; nm, nuclear membrane; ph, pharynx; phf, pharyngeal fold; sf, sperm flagellum; sh, sperm head; sp, sperm; va, acrosomal vesicles of anterior cytoplasm.
the proboscis, in a circumferential nerve ring around the collar
region, and within the trunk region as a longitudinal mid-ventral
condensation beneath the esophagus continuing posteriorly into
two main nerve strands (Figures 3A–G, 5D, E, G, 6; online 3D
movie of anti-serotonin IR). At the level of the collar region the
nervous system constitutes the typical collar cord that lies in a
subepidermal position running within the dorsal septum of the
mesocoelic cavity, thereby passing through the mesocoelic cavity
within the anterior ridge of the collar (Figures 2, 3A, B, F, G). The
collar cord (50 μm in total length, 3 μm wide, 5 μm high) is
surrounded by ECM and composed of numerous neurites passing
the cord in longitudinal direction (Figure 3F); no neuronal somata
present within collar cord (Figure 3F, G, 5D, E, G). The collar
cord continues into a basiepidermal nerve plexus within the
posterior ridge of collar region (Figure 2, 3A, 5D, G, see also
online 3D movie of anti-serotonin IR); neuro pores absent.
Anteriorly, the collar cord connects to the dorsal proboscis stem
(Figure 2), showing a condensed area of basiepidermal neurites
(Figures 3C, 5D–G, 6A, B–E). Serotonin-like and anti-FMRF-
amide like immunoreactivity (IR) was found throughout the
nervous system, the serotonergic nervous system being the most
distinct. Tubulin IR in nerves could only occasionally be
distinguished from IR in cilia (e.g., Figure 6A), and is not
described herein. Basiepidermal serotonergic and FMRFamide
geru tes run along the proboscis showing a condensation (npl) in
the nerve net at the base of the proboscis, i.e. the proboscis stem

Figure 5. Meioglossus psammophilus gen. et sp. nov., confocal laser scanning microscopy, Z-stack projection images showing
musculature (phalloidin staining), cilia (anti acetylated α-tubulin IR), nerves (anti α-tubulin and serotonin IR). A. Two zooids of
specimen showing paratomy, paratype ZMUC-ENP-3, dorso-lateral view. Triple staining of cilia, muscles and nervous system showing F-actin (green)
and anti acetylated α-tubulin IR (blue) and anti-serotonin IR (red). B. Proboscis and collar cilia, paratype ZMUC-ENP-43, anti acetylated α-tubulin IR,
depth coded. Depth scale follows the colors of the spectral light (blue to red). C. Anterior part of specimen from A, musculature, depth coded Z-stack.
D. Proboscis, serotonergic nervous system (SNS) of A, depth coded Z-stack. E. Whole single specimen, ZMUC-ENP-47, double staining, anti acetylated
α-tubulin IR (blue) and anti serotonin IR (red). Same specimen used in 3D isosurface reconstruction in attached Movie S3. F. Close up of serotonergic
perikarya from proboscis of G, depth coded. G. Whole specimen, ZMUC-ENP-47, SNS, depth coded. Abbreviations: apvn, anterior perikarya of ventral
nerve net; cb1, cb2, 1. & 2. ciliary band; cm, circular muscles; co, collar region; es, esophagus; lm, longitudinal muscles; map, muscular anchoring
point; mg, midgut; MHC, midgut-hindgut constriction; mo, mouth opening; mpvn, median perikarya of ventral nerve net; nc, neurochord (collar); npl,
nerve plexus; om, oblique muscles; pb, proboscis; pcb2, perikarya of second ciliary band nerves; pcm, proboscis circular muscles; ped, perihemal
diverticula; pnc1–4, posterior perikarya 1 to 4 of neurochord; plm, proboscis longitudinal muscles; pln, nerves innervating proboscis longitudinal
muscles; ppb, perikarya of proboscis; ppvn, posterior perikarya of ventral nerve net; TF, transverse fission zone; vn, ventral nerve net (forms two
ventral ‘cords’).
doi:10.1371/journal.pone.0048529.g005
The serotonergic neurites seemingly originate at a dense anterior assemblage of about 30 serotonergic perikarya (Figures 5A, D, E, G, 6A, D) and a median ring of about 20 serotonergic perikarya (Figures 5A, D, G, 6D). The latter plexus also shows 50+ FMRFamideergic perikarya (Figures 6B–C, G–H). Several neurons are distally ciliated (Figure 5F) indicating that these may function as sensory neurons, whereas others may be secretory or motor neurons innervating the proboscis musculature. At the posterior border of the collar four seemingly sensory serotonergic perikarya connected to cilia (pnc, Figure 5A, D–E, G; see also online 3D movie of specimen shown in Figure 5E) give rise to four neurites, fusing anteriorly with the collar cord. The collar cord shows a dense serotonergic and FMRFamideergic IR throughout its entire length along the collar to the base of the proboscis. At the mid-collar a ring of 20–30 serotonergic and FMRFamideergic perikarya are found beneath the dense ciliary band lining the circumbuccal groove (pcb2, Figures 5A, D–E, G, 6D, G–H). Posterior to this ciliary band in the anterior trunk (surrounding the esophagus) dense aggregations of glandular cells are revealed by the presence of tyrosinated tubulin IR (Figures 6A, D, E). The serotonergic basiepidermal nerve net of the anterior trunk is condensed into a mid-ventral cord beneath the esophagus, separating into two ventral bundles at the anterior border of the gut. Each bundle consists of about ten serotonergic neurons with peripheral perikarya innervating the proboscis longitudinal muscles (Figures 5D–E, G, 6A, E; see also online 3D movie of specimen shown in Figure 5E). The serotonergic perikarya and associated neurites of the two ventral trunk bundles are organized in pairs along the dorso-lateral side of trunk. The antero-most pair consists actually of two clusters, each comprising 6–7 serotonergic perikarya. The following 4–5 pairs consist of a
single serotonergic perikaryon on each side, the last pair reaching the tail (Figure 5E, G).

Reproduction is presumably gonochoristic as in other enteropneusts, but only males were found. Reproduction seemingly seasonal with fertile males found in Belize in January and April (nearly all specimens examined were fertile) and in Bermuda in June but not in October. Sperm distributed in up to four pairs of dorsal testes or freely in the metacoel along the entire intestine; also present in the posterior zooid, during paratomy of fertile animals (Figures 1A–D, H–J, 4D–H, J; see also online LM movie of live animal). Sperm head arrow- or bullet-shaped (2–3 μm long, 0.5–1 μm wide; Figures 1H–J, 4D, F–H, J). Central nucleus with electron-dense core and less dense periphery, sometimes with ‘lamellar’ appearance possibly due to crystallization (Figure 4F, G, H, J). Nucleus surrounded by indistinct nuclear membrane (nm, Figure 4H) and cytoplasm (cy); dense basally (ba) and anteriorly with acrosomal vesicles (va, Figure 4F, H). No mitochondria detected. Centriole and anchoring apparatus (Figure 4F) basal to what appears to be the very long, stiff, possibly degenerated or undeveloped flagellum (up to 30 μm long, 0.5 μm wide), since no microtubules were identified (Figures 1I, 4D–H, J).

A mode of asexual reproduction unique among Enteropneusta was observed in specimens from all collecting sites, during all seasons (in up to one third of the specimens per site). Fertile as well as unfertile individuals divided by paratomy. Paratomy is a form of transverse fission, where the secondary individual develops to almost full size following the anterior-posterior axis in a chain of zooids, before fission (Figures 1C, E, G, 5A). The intestinal system continues through the second zooid (Figures 1C, 5A), seemingly functioning and providing nutrition to the second zooid until shortly before separation (Figure 1G), where the organ differentiation (‘regeneration’) is nearly complete.

The complete 18S rRNA and a fragment of the mitochondrial 16S rRNA was sequenced from a specimen from Windsor Beach, Bermuda (GenBank Accession numbers in Table 2). Phylogenetic analyses based on 18S rRNA and 16S rRNA showed no identity of *M. psammophilus* gen. et sp. nov. to any previously sequenced hemichordate, including *Glossobalanus* and *Ptychodera* (Ptychoderaeidae), which are the only previously recorded genera from shallow sandy bottoms around Bermuda and the Caribbean Sea. *Meioglossus psammophilus* gen. et sp. nov. forms a clade with the Harrimaniidae genera *Harrimania*, *Protoglossus*, *Saccoglossus* and *Saxipendium* in all analyses (Figures 7 and 8, Figure S1). The exact position of this species received only low nodal support, either nesting within the family as sister to *Harrimania planktophilus* and *Protoglossus koehleri* (in the maximum likelihood analysis, Figure 7) or
as sister group to all other harrimaniids (in the parsimony direct optimization analysis, Figure 8).

**Remarks**

*Meioglossus psammophilus* gen. et sp. nov. shows a closest resemblance morphologically as well as phylogenetically to members of Harrimaniidae. Ptychoderid apomorphies such as the characteristic hepatic sacs or gonadal wings are lacking. Like several members of Harrimaniidae, the new species has two proboscis pores and lacks circular musculature in the posterior trunk [65]. *Meioglossus psammophilus* gen. et sp. nov. resembles *Harrimania kupfferi* von Willemoes-Suhm, 1871 in the presence of elongated, arrow-shaped sperm heads (Figures 1H–J, 4F, H) [66], but the phylogenetic analyses do not support a sister group relationship of the two species. Thus, *Meioglossus* gen. nov. is here described as a new genus, since it differs significantly from adult males of all described harrimaniid genera and does not nest within any harrimaniid genera included in this analyses. It further differs from all known adult harrimaniid genera in its minute adult size, the single thin ring of longitudinal muscles in the proboscis, the absence of stomochord and neck skeleton, and the asexual reproduction by paratomy.
Table 2. Taxon sampling and sequences included in phylogenetic analyses.

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<td>MCZ DNA101771/4</td>
<td>JF900485</td>
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<td>JN886751</td>
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Harrimaniidae

Harrimania planktophilus

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
AF236799 | EU728421 | Cameron et al. 2000 | British Columbia, Canada

Harrimania kupfferi

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
MCZ DNA103688 | JF900487 | JX855286 | This paper | Denmark

Meioglossus psammophilus gen. et sp. nov.

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
ZMUC-ENP-1 | JF900488 | JX855287 | This paper | Bermuda

Saccoglossus kowalevskii

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
L28061 | - | Turbevile et al. 1994 | |

Saccoglossus pusillus

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
AF236800 | EU728422 | Cameron et al. 2000 | British Columbia, Canada

Saccoglossus bromphenolosus

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
AF236801 | - | Cameron et al. 2000 | Washington, USA

Protaglossus koehleri

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
EU728432 | EU728420 | Cannon et al. 2009 | Australia

Saxipendium coronatum

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
EU728433 | EU728423 | Cannon et al. 2009 | SE Pacific Rise

Saxipendium sp. 1 (D176-A11)

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
JN886774 | JN886756 | Osborn et al. 2012 | |

Saccoglossus kowalevskii

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
L28054 | - | Turbevile et al. 1994 | |

Saccoglossus pusillus

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
AF236800 | EU728422 | Cameron et al. 2000 | British Columbia, Canada

Saccoglossus bromphenolosus

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
AF236801 | - | Cameron et al. 2000 | Washington, USA

Protaglossus koehleri

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
EU728432 | EU728420 | Cannon et al. 2009 | Australia

Saxipendium coronatum

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
EU728433 | EU728423 | Cannon et al. 2009 | SE Pacific Rise

Saxipendium sp. 1 (D176-A11)

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
JN886774 | JN886756 | Osborn et al. 2012 | |

Spengelidae

Glandiceps hacksi

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
JN886773 | JN886755 | Osborn et al. 2012 | |

VERTEBRATA

Plethodon cinereus

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
DQ060806 | - | Turbevile et al. 1994 | |

ECHINODERMATA

Branchiostoma lanceolatum

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
AY428817 | JX855284 | Giribet et al. 2004/This paper | |

Neogymnocrinus richeri

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
AY275895 | - | Cohen et al. 2004 | |

Cucumaria miniata

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
DQ777082 | - | Janies et al. 2011 | |

Paracentrotus lividus

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
AY428816 | - | Giribet et al. 2004 | |

Patiria pectinifera

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
AB084551 | - | Matsubara et al. | |

Ophiopholis aculeata

Voucher | 18S rDNA | 16S rDNA | Publication
---------|-----------|-----------|------------
DQ060806 | - | Janies et al. 2011 | |

Table 2. Cont.

Discussion

The finding of an enteropneust that remains meiofaunal during its entire life cycle - the smallest acorn worm known to date - highlights the hidden diversity inhabiting the interstitial environment. Its resemblance to juveniles of other species has resulted in this species being overlooked by zoologists [64] and suggests that this or additional species may be found in other localities. Meioglossus psammophilus gen. et sp. nov. is also, with its 0.6 mm in maximum size, among the smallest solitary deuterostomes of about 1 mm [22–30], only comparable in size to some acoelomorphs.

Whereas various forms of asexual reproduction are found in Enteropneusta (mainly architomy), this is the first example of paratomy. In M. psammophilus gen. et sp. nov. organ differentiation takes place before fission (paratomy), leading to aligned chains of zoids (two only) with the development following the anterior-posterior axis of the parental zoid. Asexual budding as an unaligned form of paratomy is found in other deuterostomes, including ophiuroid larvae and colonial pterobranchs [55,57,67]. Reproduction by paratomy in Meioglossus gen. nov. seems independent of the presence of gametes, as it has been observed in non-fertile individuals from Bermuda (October 2007), and in the sperm-bearing specimens from Belize (January 2010). In the latter case sperm may be utilized as an energy store, as is the case in non-fertile individuals from Bermuda (January 2010). In the former case sperm may be utilized as an energy store, as is the case in non-fertile individuals from Bermuda (January 2010). In the latter possibly being one of the best-known subtropical faunas worldwide. It is also worth noting that the morphology of the studied specimens is similar in all populations (including detailed muscle and nervous system as well as paratomous reproduction) at
different locations, and different seasons. An extended distribution of the serotonergic nervous system through the entire trunk, otherwise only extending along the proboscis and collar in adult Psychodora flava [54] may also be indicative of adulthood; yet this hypothesis warrants further studies of additional species (especially harrimaniids). It is also remarkable that the new species exhibits asexual reproduction by transverse fission, only known from adult stages of other enteropneust species with asexual reproduction (yet as archiomy rather than paratomy) [56,58,59]. The most obvious argument for adulthood of male M. psammophilus is possibly the obvious lack of growth during 2 weeks of live observations, whereas enteropneust juveniles of comparable size are known to approximately double their length or more within the same time frame [53,68,69].

The finding of males only, despite intensive collecting effort, is however puzzling. Females may remain undiscovered due to a difference in their seasonality to males or a short reproductive season, which is known for e.g., the enteropneust Psychodora flava [54]. Alternatively, the females may live in a different habitat, such as in the water column, at a greater depth, as commensals or parasites on macrofauna, or buried deeper in the sediment. At least six tornaria larvae (including the giant Planctosphaera) not matched to their adults are known from the Gulf Stream [72,73]. Sequential hermaphroditism is known for several marine animals [74], but hermaphroditism has never previously been reported in enteropneusts, yet does exist in Petrombranchia [55]. Dwarf males are known in a number of marine taxa (not in Hemichordata), but are usually quasi-parasites typically cohabiting with females in varying degrees of intimacy [49,75,76]. The small number of spermatozoa in M. psammophilus gen. et sp. nov. and the poorly developed sperm tails suggest that sperm may be transferred directly to the female or egg mass rather than indirectly spawned into the water column.

Interstitial animals are generally characterized by minute slender forms, unique ciliary patterns, and an often seemingly simple morphology [12,13]; but see a counter example in the complex morphology of Loricipoda [32]. While most macroscopic phyla have meiofaunal representatives in the interstitial environment [13], none had yet been reported for Hemichordata. This is therefore the first adult solitary meiofaunal species in this phylum. From the derived position of M. psammophilus gen. et sp. nov. it can be inferred that it evolved by miniaturization. However, it is difficult to determine whether its many simple morphological traits should be interpreted as juvenile (from an arrest of growth due to progenetic origin) or just multiple losses (several uncoordinated evolutionary events) [47,76]. Yet, taking into consideration the adaptive requirements of the interstitial milieu, favoring macroevolutionary changes [46,47,74], as well as the fact that enteropneust juveniles are already pre-adapted to this environment, it is likely that the origin of M. psammophilus gen. et sp. nov. is progenetic, as it has been proposed for other meiofaunal deuterocestomes [26,29].

**Hemichordate phylogeny**

Our study includes the most comprehensive phylogeny of the phylum Hemichordata and corroborates previous hypotheses of enteropneust paraphyly, as Petrombranchia appears as the sister group of the enteropneust family Harrimaniidae (Figure 7; ML bootstrap proportion (BP) = 97%). This result has found support in earlier studies using 18S rRNA and Bayesian inference [7] or combined 18S and 28S rRNA using maximum likelihood [3], but has been contradicted by a recent study, which finds no support for a sister group relationship of Petrombranchia and Harrimaniidae [8], using a very similar data set to the one we use here. We therefore redid several analyses using alternative alignment methods and trimmings with GBLOCKS (results not shown), but could not recover their topology lacking support for a Petrombran-

**Materials and Methods**

**Ethics statement**

**Morphological study**

Animals were examined alive and fixed for various morphological studies and DNA sequencing following published methods [48,78] (see Table 1). Live images and video-recordings were made with a Sony HDR-XR520 mounted on a Zeiss AX10 microscope with DIC as well as an Olympus C-5060 mounted on a Leica Dialux 20 microscope with phase contrast. The musculature and nervous system were investigated with F-actin staining (FITC-labeled or AlexaFlour 488 phalloidin, Sigma P-5282 or Invitrogen A12379) and immuno-staining (monoclonal mouse antibody, Jackson Immunoresearch 115-175-062), monoclonal mouse anti-acetylated α-tubulin Sigma T 6793 (CY5-labelled secondary antibody, Jackson Immunoresearch) and immuno-staining (monoclonal mouse anti-tyrosinated tubulin Sigma T 6793 (CY5-labelled), polyclonal rabbit anti-serotonin Sigma: S5545 (5-HT) and anti-FMRF-amid ImmunoStar: 20091 (FITC- or TRITC-labeled secondary antibodies, Sigma F0382 or F5268) following published protocols [48,49,78](Table 1). Stained specimens were examined with a Leica TCS SP5 confocal laser microscope at the Danish Technical University or at SUND (courtesy of M. Givskov & T. Bjarreholt). Z-stack projections of CLSM images and 3D rendering analyses were performed with Leica LASAF computer software or Imaris®×64 6.00 (Bitplane AG, Zurich, Switzerland). Computed 2D images were further optimized with Adobe Photoshop CS4 and Adobe Illustrator CS4 for presentation.
Specimens were prepared for histological sectioning, transmission electron microscopy and scanning electron microscopy according to published methods [40] (Table 1). Complete longitudinal serial sections of 0.5-μm thickness for light microscopy of three adult specimens (ZMUC-ENP-27 to 29) were sectioned on a Leica Ultracut S; two nearly complete transverse (ZMUC-ENP-30, 34) plus three sagittal series (ZMUC-ENP-31, 32, 33) all based on 0.5–1 μm-thick sections were further sectioned on various Leica ultramicrotomes. All semi-thin sections were stained with toluidine blue. About a thousand longitudinal and transverse thin sections for TEM were cut from six adult specimens on various ultra-microtome models including a Leica Ultracut 7 (see Table 1). Ultra thin sections were stained with 2% uranylacetate and 2.5% lead citrate and examined with a JEM-1010 at BIO, NATFAK and Philips 300 at SUND, University of Copenhagen and a ZEISS 902 at CIUS, University of Vienna. Light microscopic images of semithin sections were recorded with a digital camera mounted on a Nikon Eclipse E800 compound microscope or with a DP71 digital camera mounted on an Olympus BX50 compound microscope. Light microscopic images from a complete longitudinal series were aligned using open source software Imodalign on a Linux operating computer [79]. Based on the resulting stack of images a 3D-model of the anatomy of the main organ systems was created in Amira 5.4.1 software (Visage Imaging, Berlin, Germany). Scanning electron microscopy images of critical point dried and platinum coated specimens were taken with a JEOL JSM-6335F Field Emission scanning electron microscope at SNM, NATFAK, University of Copenhagen.

Molecular study

Genomic DNA was isolated from *M. psammophilus* gen. et sp. nov. from Bermuda using the DNeasy Tissue Kit (Qiagen) and the complete 18S rRNA and a fragment of the mitochondrial 16S rRNA were sequenced (GenBank accession numbers in Table 2). Although we attempted to sequence other specimens from Bermuda and Belize, only one yielded good quality DNA, and amplified for multiple markers. Another specimen amplified for only a short gene, histone H3.

A total of 52 18S rRNA sequences were obtained from previous studies [5–8] or were sequenced for this study to span the hemichordate diversity. The sampling includes members from all described families, and a large diversity of the recently discovered Torquatoratoridae [5,77]. We only used nearly-complete 18S rRNA sequences, with the exception of rhabdopleurids, for which no complete 18S rRNA sequences were available. Sequencing 18S rRNA followed standard protocols and primers described elsewhere [80]. Primers and 5′ and 3′ edges were trimmed to accommodate partial sequences from some of the studies listed above, for a total unaligned length of between 1707 and 1831 nucleotides. We avoided the sequence of *Stereobalanus canadensis* (GenBank # EU728434) as it is of questionable origin. Likewise we obtained 36 16S rRNA sequences, but no 16S rRNA is currently available for any members of Pterobranchia, and therefore the 16S rRNA data set has no bearing in the debate of enteroneust monophyly. For this reason, we analyzed it independently, with the sole aim of testing the affinity of *M. psammophilus* gen. et sp. nov.

Phylogenetic analyses - Probabilistic approaches

Maximum likelihood (ML) analyses of the 18S rRNA data set were conducted on a static alignment generated by MUSCLE v. 3.6 [81] with default parameters, yielding 2034 aligned positions, which were reduced to 1570 positions after treatment with Gblocks 0.91b [82]. The same treatment was given to the 16S rRNA data set, which included 603 aligned positions, from which 510 were retained after treatment with Gblocks. Each individual data set was then submitted to ML analysis using RAxML v. 7.2.7 [83] through the CIPRES v. 3.5 gateway, using 64 processors in a cluster housed at the National Center for Supercomputing Applications (University of Illinois). A unique GTR model of sequence evolution with corrections for a discrete gamma distribution (GTR+F) was specified for the data. Nodal support was estimated via the rapid bootstrap algorithm (1000 replicates) using the GTR-CAT model [84].

Phylogenetic analyses - Dynamic homology under parsimony

A direct optimization [85] analysis for the 18S rRNA was conducted in POY v. 4 [86] under parameter set 3221 (indel opening = 3; indel extension = 1; transversions = transitions = 2) using a timed search with TBR branch swapping, tree fusing and ratcheting, searching for 6 hours and accumulating all best trees for each replicate. The 33 resulting trees were submitted to a second round of tree fusing. The search evaluated 5 independent repetitions with ratchet and fusing for 7 generations. The shortest tree, at 4456 weighted steps, was found 2 times. Nodal support was evaluated using 1000 jackknife [87] replicates with a probability of deletion of each character of 0.36 (Figure 8). Since resampling techniques may be meaningless under dynamic homology, different strategies can be applied. Dynamic characters can be converted to a static set, but this tends to inflate support values, as it is based on the implied alignment that favors that topology. Instead, we resample dynamic characters by both using the number of predetermined fragments (6 fragments for 18S rRNA) as well as the command auto_sequence_partition, which evaluates each predetermined fragment. If a long region appears to have no indels, then the fragment is broken inside that region, effectively increasing the number of characters than can be resampled.

Supporting Information

Figure S1 Optimal maximum likelihood tree obtained in RaXML under GTR+F for the 16S rRNA data set (−logL = −4667.030968). Values on nodes indicate bootstrap support values above 50%; an asterisk indicates a value of 100%. (TIF)

Figure S2 *Meioglossus psammophilus* gen. et sp. nov., 3D-reconstruction of the anatomy of the main organ systems. Click on image to activate 3D model. (PDF)

Movie S1 *Meioglossus psammophilus* gen. et sp. nov., recording through dissecting microscope of extracted, live animals in petri dish. (MP4)

Movie S2 *Meioglossus psammophilus* gen. et sp. nov., recording through compound microscope of live animal, showing paratomy, ciliary beating, intestinal system, sperm. (MP4)

Movie S3 *Meioglossus psammophilus* gen. et sp. nov., confocal laser scanning microscopy of proboscis musculature, 3D rendering of Z-stack performed with Imaris 6.02 software. Movie showing first all 3 channels of signal with cilia in blue (anti acetylated α-tubulin IR), serotoninergic nervous system in red (anti serotonin IR) and musculature in green (phalloidin), thereafter only musculature (green). (MP4)
Movie S4 Mioglossus psammophilus gen. et sp. nov., confocal laser scanning microscopy of collar and anterior trunk musculature, 3D rendering of Z-stack performed with Imaris 6.02 software. Movie showing first all 3 channels of signal with cilia in blue (anti acetylated α-tubulin IR), serotonergic nervous system in red (anti serotonin IR) and musculature in green (phalloidin), thereafter only musculature (green).

(MP4)

Movie 5 Mioglossus psammophilus gen. et sp. nov., confocal laser scanning microscopy, 3D isosurface reconstruction of serotonergic nervous system from Z-stack performed with Imaris 6.02 software. Movie showing first direct signal of cilia in blue (anti acetylated α-tubulin IR) and serotonergic nervous system in red (anti serotonin IR). Thereafter isosurface manipulation of anti serotonin IR in neurites and perikarya. Neurocord (collar cord) and condensed anterior ventral nerve net colored orange, remaining parts red. Perikarya of proboscis colored green; perikarya 1 to 4 of neurochord on posterior collar colored dark blue; perikarya of second ciliary band nerves colored purple and medium blue; perikarya of ventral nerve net colored light blue.

(MP4)

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Author Contributions
Conceived and designed the experiments: KW WS GG. Performed the experiments: KW WS AHS GG SK-S. Analyzed the data: KW AHS GG SK-S. Contributed reagents/materials/analysis tools: KW WS AHS GG SK-S. Wrote the paper: KW GG.

References