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► **To cite this version:**

Hélène Laguerre, Grégory Raymond, Patrick Plan, Nadia Améziiane, Xavier Bailly, et al.. First description of embryonic and larval development, juvenile growth of the black sea-cucumber *Holothuria forskali* (Echinodermata: Holothuroidea), a new species for aquaculture in the north-eastern Atlantic. *Aquaculture*, 2020, 521, pp.734961 -. 10.1016/j.aquaculture.2020.734961 . hal-03489603

HAL Id: hal-03489603

<https://hal.science/hal-03489603>

Submitted on 7 Mar 2022

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1 First description of embryonic and larval development, juvenile growth of 2 the black sea-cucumber *Holothuria forskali* (Echinodermata: Holothuroidea), a 3 new species for aquaculture in the North-Eastern Atlantic 4

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17 18 19 ABSTRACT

20
21 *Holothuria forskali* (Delle Chiaje, 1823), also called the “black sea cucumber or cotton spinner”, is a native species from the
22 North East Atlantic Area and the Mediterranean Sea. This holothurian is newly targeted to supply the Asian Market. In this context,
23 developing aquaculture is important to prevent risks of over fishing. This paper describes the first successful reproduction, larval
24 rearing, and juvenile growth of *H. forskali* performed in captivity. Reproduction of *H. forskali* was observed in April 2018. The
25 reproductive behavior was similar to those observed in other species. The auricularia stage hatched after 4 days and lasted more than
26 30 days. Pentactula and metamorphosis to the benthic life was obtained after 40 days. Juveniles have been observed only after 90
27 days and measured 8 mm long. Juvenile growth was slow (0.1 mm/day) for this first breeding. This first description of *H. forskali*
28 breeding and rearing in hatchery is encouraging for a new innovative and sustainable aquaculture.
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31 ARTICLE INFO

32 Keywords: *Holothuria forskali*, sea cucumber, aquaculture, spawning, larvae, embryonic development, metamorphosis, juvenile growth.

34 1. Introduction

35 Holothurians (Echinodermata: Holothuroidea), known as “sea cucumbers” or “beche-de-mer”, are popular luxury
36 food in Asia, called “trepang”, and represent an economic important market as high value seafood products
37 (Battaglene et al., 1999; Chen, 2004; Conand, 2004; Purcell et al., 2012a; Purcell et al., 2013). They are also used in
38 traditional medicine for their nutritional virtues (Chen, 2004; Vergara & Rodriguez, 2016) and in medicine,
39 pharmacology and in cosmetics for their bioactive compounds with anti tumoral, anti-oxidant and anti-inflammatory
40 properties actually explored and valued (Janakiram et al., 2015; Kiew & Don, 2012; Kumar et al., 2007; Mena-Bueno
41 et al., 2015; Santos et al., 2015).

42 The increasing demand of commercialized species and the uncontrolled exploitation of wild stocks in the last
43 decades have led to a collapse of natural resources, classifying some species in threatened species (Anderson et al.,
44 2011; Choo, 2008; Devanadera et al., 2015; Hamel et al., 2003; Otero-Villanueva & Ut, 2007; Purcell et al., 2012b;
45 Purcell et al., 2013; Ramofafia et al., 2003). Thereby, developing aquaculture is a sustainable way to supply the market
46 demand and to create new economic activities in coastal areas. Moreover, sea cucumbers have an important ecological
47 role in marine ecosystems, due to their feeding behavior as deposit feeders and detritivorous animals (Purcell et al.,
48 2016). They are candidates for aquaculture bioremediation and for integrated multi-trophic aquaculture (Chopin et al.,
49 2012; MacDonald et al., 2013; Paltzat et al., 2008; Slater & Carton 2007; Slater & Carton 2009; Tolon et al., 2017;
50 Yokoyama, 2013; Zamora & Jeffs, 2013; Zhou et al., 2017).

51 Aquaculture of Indo-Pacific species have been developed since the 80s and industrial farms produce sea cucumber
52 juveniles such as *Apostichopus japonicus* in China and Japan (Akamine, 2004; Chen, 2004; Ito & Kitamura, 1998;
53 Soliman et al., 2013), or *Holothuria scabra* in the Indo-Pacific Region (Altamirano et al., 2017; Battaglene et al.,
54 1999; Hamel et al., 2001; Knauer, 2011; Kumara & Dissanayake, 2017; Mazlan & Hashim, 2015; Yan et al., 2012).

55 Due to decrease in natural stocks of tropical species, European species of *Holothuroidea* are targeted by the Asian
56 Market (Gonzalez-Wanguemert et al., 2018; Hamel & Mercier, 2008); Atlantic and Mediterranean species are now
57 subject to an important fishing, inducing illegal fishing and effects on biometry and genetic structure
58 (Dominguez-Godino et al., 2016; Gonzalez-Wanguemert et al., 2015; Gonzalez-Wanguemert & Godino, 2016). Only
59 few species of European species have been described for hatchery and cultivating procedures, in a pilot-scale, *H.*
60 *arguinensis* (Dominguez-Godino et al., 2015), *H. tubulosa* (Rakaj et al., 2018), *H. mammata*, (Dominguez-Godino and
61 Gonzalez-Wanguemert, 2018) and *H. polii* (Rakaj et al., 2019).

62 *H. forskali* (Delle Chiaje, 1823) is a native unexploited species from Brittany Coast (France) and can be found in the
63 North East Atlantic Area and Mediterranean Sea, in rocky sea beds, from 1 to 100 meters depth. This species is
64 difficult to maintain in captivity because of its behavior in case of stress. It ejects - as a defensive strategy - cuvierian
65 tubules and sometimes even several organs that can lead to death, even if *H. forskali*, like the other Holothurians and
66 Echinoderms, are able to regenerate most of its organs. *H. forskali* is a deposit feeder as the majority of Holothurians,
67 and ingest sediment containing fresh or detrital organic matter (Purcell et al., 2016; Massin & Jangoux, 1976; Roberts
68 et al., 2000). This gonochoric species has an annual reproduction cycle with a synchronous spawning for male and
69 female in spring in the Atlantic Area (Despalatovic et al. 2003; Santos et al., 2015; Tuwo & Conand 1992; Tuwo &
70 Conand 1994). However, there is no exhaustive references on reproduction behavior, embryonic and larval
71 development of *H. forskali*.

72 We report herein for the first time the reproductive behavior, embryonic and larval development, and juvenile
73 growth of *H. forskali* in captivity.
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75 2. Material and methods

76 2.1 Broodstock collection and maintenance

77 Adults of *H. forskali* (n=36, mean weight = 322.78 ± 68.27g) were collected at Brezellec (West Coast of Brittany,
78 France: 48°4'15.15"N and 4°39'45.29"W) by scuba diving at 5 to 12 meters depth on 5th of April 2018 (fig. 1, the
79 geographic map was obtained from the French national website www.geoportail.gouv.fr) and the seawater
80 temperature was 12°C. Broodstocks were transferred directly in a 30 L box to the hatchery of the marine experimental
81 station of Agrocampus Ouest in Beg-Meil (Fouesnant, France). Broodstocks were placed in a 250 L tank and were
82 maintained in flowing 5 µm filtered seawater at 14°C prior to thermal induction of spawning. Animals were carefully
83 handled to avoid expulsion of cuvierian tubules and organs such as gonads.
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91 **Fig. 1.** Sampling location (zoom with a white box) and habitat of the sea-cucumber *H. forskali* (black arrows) in West Brittany, France
92 (site located with a red box).

93 2.2 Macroscopic and microscopic examination of the gonadal tubules

94 Before induction of spawning, gonads were removed from the animals by dissection to determine the maturity
95 stages: immature (I), resting (II), maturing (III), pre-spawning (IV) and post-spawning (V) (Ramofafia et al., 2000;
96 Ramofafia et al., 2003; Santos et al., 2015; Tuwo & Conand, 1992). Macroscopic and microscopic observations were
97 performed on gonadal tubules, in order to ensure the maturity stage: primary (T₁), secondary (T₂), growing and fecund
98 (T₃, T₄), and spend tubules (T₅) (Tuwo & Conand, 1992).

99 2.3 Induction of spawning by thermal stimulation and fertilization

100 Induction of spawning was performed by thermal stimulation on the 6th of April 2018. Water temperature was
101 quickly raised to 19°C by continuous flow of 1µm filtered seawater, and was maintained at 19°C until spawning.
102 Photos and videos were taken during spawning to describe spawning behavior. Fertilization in the tanks was
103 performed and monitored.

104 2.4 Embryonic and larval breeding

105 When spawning occurred, fertilized eggs were removed from the tank with 80µm sieve, and washed with seawater.
106 The seawater used for embryonic and larval rearing was sand filtered, then filtered with 1µm filter bag and sterilized
107 by UV system. Eggs were observed and incubated at 18°C (±1°C) for 12 hours in 10 L flat bottom trays in closed-

108 water systems, before larval breeding, at a density of approximately 10 embryos/ml. Embryos were sampled and were
109 observed every hour to describe cell divisions, and measured under a microscope equipped with a micrometric
110 eyepiece.

111 After incubation, eggs were transferred to hatchery 35 L and 100 L aerating tanks and maintained in closed-water
112 systems at 17°C ($\pm 1^\circ\text{C}$), at a density of 5-10 larvae/ml, with natural photoperiod. Larvae were sampled and observed
113 daily to describe the larval development (size, color, organs formation). Seawater of hatchery tanks was renewed 3
114 times a week: twice with partial seawater change (50%) and once with full change (100%), using a 120 μm mesh
115 sieve. Water temperature was daily monitored, and 5 ml was collected to observe and describe larval development.
116 Between the late Gastrula and the early Auricularia stage, larvae were fed daily with a mixture of the microalgae
117 *Isochrysis galbana* and *Chaetoceros muelleri* (1:1), at a final concentration from $5 \cdot 10^3$ to 10^4 cell.mL⁻¹. From the late
118 Auricularia stage until Doliolaria stage, they were daily fed with *I. galbana* and *Skeletonema costatum* (1:1).
119 Microalgae were cultivated in Conway Growth Medium, successively in 500 mL, 2 L, 10 L Erlenmeyers and 310 L
120 cylinder, using the method of the batch culture of microalgae. Salinity was maintained at 35 PSU.

121 2.5 Metamorphosis and juvenile breeding

122 At Pentactula stage, larvae were transferred in a micro-nursery with airlift systems, in 300 mm diameters sievers
123 containing Plexiglas plates, previously striped with a wire brush and colonized by a fouling of periphytic microalgae.
124 Plates of slightly roughened Plexiglas, which were vertically stacked in the water column with each sheet separated by
125 a spacer. Tanks were placed in black during metamorphosis – settlement at ambient temperature, 18°C ($\pm 1^\circ\text{C}$).
126 Microalgae *S. costatum* and *C. muelleri* (2:1) were daily added 2 days after settlement. When juveniles were observed
127 in tanks, fish micropellets (Carp fish feed from Alltech Coppens, The Netherlands) were distributed once a week.
128 Approximate measurements were made with a ruler under the binocular magnifier.

129 3. Results

130 3.1 Gonadal morphology in mature broodstock

131 Gonads of mature broodstock appeared as a well-developed tree constituted by a multitude of branched tubules,
132 converging towards the gonadal basis and attached to the body wall. The gonadal basis was divided into primary
133 tubules, and then bifurcated in secondary ramifications and then fecund tubules during the spawning period. Gonadal
134 tubules in mature female was dark orange to red and white to pale pink in mature male (fig. 2 A-B). In April and
135 during the spawning period, mature gonads were observed, corresponding to stage IV: mature and pre-spawning
136 gonads (Santos et al., 2015; Tuwo & Conand, 1992). Gonads occupied a large place in the body cavity and tubules
137 were more than 10 centimeters long and 1 to 2 mm in diameter, corresponding to class T4 fecund tubules (Tuwo &
138 Conand, 1992). Male mature tubules were filled with agglomerated spermatozoa, composed by a tail and a head (fig.
139 2C). Microscopic examination of female tubules shown mature and densely packed ovaries (fig. 2D-E), composed by
140 mature oocytes (165 μm in diameter) with their germinal vesicle (50-55 μm in diameter) and enclosed with their
141 follicle. The newly released oocytes had lost their follicle coat and were surrounded by a 20 μm -thick translucent jelly
142 layer. The nucleus (5 μm in diameter) was well visible in the germinative vesicle (fig. 2F).

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150 **Fig. 2.** Macro- and microscopic morphology of pre-spawning gonadal tubules in female (A, D, E, F) and in male (B, C) of *H.*
151 *forskali*. A: Macroscopic aspect of mature gonadal tubule in female (T4 fecund tubules, stage IV pre-spawning). B: Macroscopic
152 aspect of mature gonadal tubule in male (T4 fecund tubules, stage IV pre-spawning). C: active spermatozoa (spz) with a focus on
153 spermatozoa morphology, tail (tl) and head (hd) in the black box. D-E: Microscopic morphology of ovarian tubules and oocyte:
154 mature vitellogenic oocytes (vo) with their follicle (f), and germinal vesicle (vg). F: view on mature oocyte with a well-visible
155 nucleus (nc) in the germinative vesicle (vg), and the translucent jelly layer (tjl) around the oocyte.

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157 3.2 Spawning behavior

158 Spawning started in the night of the 8th of April 2018, after a 2 day- thermal stimulation. Prior to spawning, male and
159 female climbed on tank walls, to the upper water level, and then extended and erected the anterior region of their body,
160 ventral face in front of the surface (fig. 3A). More than half of their body sought the standing position during
161 spawning. Male and female ejected their gametes by the gonopore (fig. 3B), localized dorsally above the mouth

162 (arrow, fig. 3C). Male ejected continuous streams of sperms and female streams of orange mature oocytes (fig. 3C, fig.
163 4A). Male and female performed oscillations to help the dispersal of the gametes.

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Fig. 3. Posture and spawning behavior of *H. forskali*. Males and females erected their body (A) and ejected a stream of sperm (sp) or oocytes (oo) (arrows, B, C) by the gonopore. Scale bars = 3 cm.

175 Animals were spawning successively during 3 days, mainly during the night, starting at the end of the day,
176 corresponding to the decrease of photoperiod. Eggs were recovered, washed and placed in incubation.

177 3.3 Embryonic and larval development

178 The average diameter of the mature eggs released by females was $165.46 \pm 4.29 \mu\text{m}$ (n=15). Because fertilization
179 was not controlled by adding sperm, duration of fertilization can be only estimated at 30 minutes. Embryonic
180 development of *H. forskali* started with the elevation of the fertilization envelop (fig. 4, table 1) and the expulsion of
181 the polar bodies (fig. 4B). The embryonic development of *H. forskali* was radial holoblastic. The first cleavage
182 appeared 2 hours after fertilization and generated 2 equal and hemispheric blastomeres (fig. 4C, table 1). The two
183 blastomeres were symmetrically divided in the following cleavages (fig. 4D-F), egg diameters evolved from 180 to
184 $195 \mu\text{m}$ until the morula stage (table 1). The blastula (mean $193.33 \pm 7.99 \mu\text{m}$) stage was observed 24 hours after
185 fertilization, exhibiting a central blastocoele and a peripheral ciliary cover able to ensure continuous rotary movements
186 (fig. 4G). The blastula stage was the first mobile stage in *H. forskali* embryonic development. The early gastrula stage
187 (mean $242.50 \pm 8.2 \mu\text{m}$) was reached between 36 hours and 2 days after fertilization by invagination and elongation of
188 the blastula wall and evolved to the late gastrula (mean size $296.67 \pm 9.43 \mu\text{m}$) 3 to 4 days after fertilization (fig. 4H-I,
189 table 1).

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Fig. 4. Embryonic development of *H. forskali* at 17°C. A: mature spawned oocyte / unfertilized egg, and a spermatozoon (spz). B: fertilized egg with a fertilization envelop (fe) and polar bodies (pb). C: First cleavage, 2 cells egg formed with 2 blastomeres (b). D: second cleavage, 4 cells egg. E: 8 cells eggs. F: Morula. G: Rotary blastula, blastocoele (blc), ciliated cove (ci), and ectoderme (ect). H: early gastrula with blastopore (blp). I: mid gastrula. Scale bars = 100 μm .

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Table 1. Embryonic and larval development and size (mean \pm SD; N > 15; *N = 5; size range and mean in μm) of *H. forskali* at 17°C. Time is represented in weeks (w), days (d), hours (hr) and minutes (min), time after fertilization (AF).

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211 The common larval stages in *Holothuroidea* species are auricularia, doliolaria and pentactula, before metamorphosis
212 and settlement. The auricularia stage hatched 4 days after fertilization (table 1). The early auricularia was characterized
213 by a functional, well visible mouth, esophagus, cloaca (fig. 5A-B) and a ciliated band used for feeding and locomotion.
214 At this stage, the larvae was able to feed. The mean length and width were respectively $639.87 \pm 40.93 \mu\text{m}$ and 394.08
215 $\pm 89.30 \mu\text{m}$ (table 1). During the auricularia stages, the larvae continuously elongated and their size evolved from 300
216 in early stages to $1450 \mu\text{m}$ in late auricularia (table 1). The mid auricularia was obtained 7 days after fertilization (fig.
217 5C), axohydrocoel was forming, the intestine increased in size and larvae began to accumulate hyaline spheres, to
218 obtained the late auricularia stage (fig. D-E), with a mean length and width of $1060 \pm 138.83 \mu\text{m}$ and $790.29 \pm$
219 $111.25 \mu\text{m}$ respectively, the maximum length registered was $1417 \mu\text{m}$. The late auricularia was reached after 25 to 35
220 days post-fertilization, accumulated 10 well-formed hyaline spheres and the edges of the larvae were invaginating.
221 After 4 weeks, the late auricularia progressively began to compact, round and shrink down to obtain a mean length of
222 $772.33 \pm 48.61 \mu\text{m}$ at the non-feeding doliolaria stage reached 36 days after fertilization. Doliolaria larvae performed

223 rotary movements with their 5 transverse ciliary bands, hyaline spheres were aligned (fig. 5G-H). Quickly, the larvae
224 evolved towards the pentactula stage less than a week later (fig. 5I, table 1), the ultimate stage before metamorphosis,
225 and changed in behavior from a planktonic larvae to a benthic larvae. Ciliated bands disappeared the 5 tentacles were
226 well-visible and the larvae moved to the bottom of the tanks to enhance metamorphosis (fig. 5I). During
227 metamorphosis, aerating was decreased, feeding was stopped and larvae were transferred in settlement tanks.
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Fig. 5. Larval development of *H. forskali* at 17°C. A: newly hatched auricularia; intestine (int), buccal cavity (bc), esophagus (eso) and enterocoel (ent). B: early auricularia; cloaca (clo). C: Mid auricularia; ossicle (oss), axohydrocoel (axo), ciliary band (cb). D-F. Late auricularia; hyaline sphere (hs), mouth (mou), cardiac sphincter (cs). G: Early doliolaria. H: Doliolaria. I: Pentactula stage; tentacles (ten). Scale bars = 200 µm.

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239 3.4 Metamorphosis and juvenile development

240 Metamorphosis and settlement of *H. forskali* began 42 days after fertilization. Duration of settlement still remained
241 undetermined. First juveniles visible to the naked eye were observed 2 months after metamorphosis. More than 200
242 juveniles were found in the settlement tank. The body of 120-day juvenile was elongated, yellowish and translucent
243 colored (fig. 6A-B). The dermis was covered with ossicles of varying shapes and with papillae along the dorsal body
244 wall; ambulacral podia appeared in the ventral face and helped for movement on substrate. In the oral pole, 10 well-
245 ramified tentacles were present. The digestive tract was visible through the dermis and exhibit peristaltic movements.
246 Most of the juveniles had a length between 0.5 and 1.5 mm (mean size 8 mm) and presented a large heterogeneity
247 between specimens. The 150 day-juveniles began to darken and were less translucent (fig. 6C-D); ossicles, papillae
248 and podia were well-developed. The average length was comprised between 5 and 30 mm (mean size 12 mm). The
249 250-day juveniles were small replicas of adults (fig. E-H), the body color were darkening, a part of the juveniles were
250 dark brown (fig. E-F-H); the length was between 0.5 and 4 cm. The 300-day juveniles sized had a large range size
251 comprised between 1 cm and 6 cm (fig. 6I) and presented an important heterogeneity. The growth of juveniles was
252 approximately 0.1mm per day from the settlement to 300 days post-fertilization (fig. 7). This heterogeneity of juvenile
253 growth may result from the feeding system and otherwise due to the difficulty of length measurements because of the
254 retraction capacity of the body and the fragility of the juveniles during manipulations.
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Fig. 6. Juveniles of *H. forskali*. A-B: 120-day juvenile; A: dorsal view; B: lateral view; tentacle (ten), podia (pod), calcareous ring (cr), ossicle (oss), papillae (pap), anus (an). C-D: 160-day juvenile; digestive tract (dt), ramified tentacle (rten). E-H: 250-day juveniles. G: zoom on juvenile dermis. I: 300-day juveniles.

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Fig. 7. Average growth of the juveniles *H. forskali*. Grey bars represented minimum and maximum sizes, the black square the mean size and the blue line the regression line with the equation and R².

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278 **4. Discussion**

279 The purpose of this study on *H. forskali* was to describe spawning, embryonic and larval development,
 280 metamorphosis, juvenile growth, and associated breeding times in hatchery, prior to aquaculture development.

281 *4.1 Reproductive behavior and spawning*

282 Broodstocks of *H. forskali* were collected in West Brittany in April, during the breeding season as previously
 283 described in the Atlantic Region and more precisely in Glenan Archipelago (Santos et al., 2015; Tuwo & Conand,
 284 1992) and confirmed by gonadal examination of the collected broodstock. The maturation cycle of *H. forskali* differed
 285 according to the site, as described in the Adriatic Sea (Despalatovic et al., 2003) or in the Atlantic Ocean (Tuwo &
 286 Conand, 1992; Santos et al., 2015); and these variations were also recorded between different populations of *H.*
 287 *arguinensis* and *H. mammata* in the Iberian Peninsula (Marquet et al., 2017).

288 Induction of spawning is an important challenge to optimize spawning and fertilization rates in invertebrate
 289 hatchery. In hatchery culture of bivalves, different techniques for spawning induction are used: thermal shocks,
 290 thermal induction, mechanical shocks, biochemical induction, and lethal methods such as gonad laceration (Bourne et
 291 al., 1989; Helm & Millican, 1977; Helm et al., 2004; Loosanoff & Davis, 1963; Utting & Pencer, 1991). In
 292 Holothuroidea, these techniques have been used and the response to the type of stimulation could be different
 293 according to the species (Rakaj et al., 2018). Thermal stimulation demonstrated the best results during the spawning
 294 season, both for temperate species from North-Eastern and Mediterranean regions such as *H. polii*, *H. tubulosa*, *H.*
 295 *mammata* and *H. arguinensis*, (Dominguez-Godino et al., 2015; Dominguez-Godino & Gonzalez-Wangüemert, 2018;
 296 Rakaj et al., 2018; Rakaj et al., 2019) and for tropical species of the Indo-Pacific Region such as *H. scabra* (Kumara et
 297 al., 2013; Mazlan & Hashim, 2015). Others techniques have shown very contrasting results such as mechanical shocks
 298 by dry stimulation for the tropical species (Hu et al., 2013; Huang et al., 2018), thermal shocks (Battaglione et al.,
 299 2002; Morgan, 2009; Rakaj et al., 2018) or phytoplankton induction (Dominguez-Godino & Gonzalez-Wangüemert,
 300 2018; Hu et al., 2013; Mazlan & Hashim, 2015). Otherwise, artificial induction of oocyte maturation by chemical
 301 inducers or by maturation inducing biochemical fractions from echinoderms shown high efficiency on Holothuroidea
 302 (Léonet et al., 2009; Mercier & Hamel, 2002) and on *H. forskali* (Léonet et al., 2009), but this technique requires the
 303 sacrifice of a large number of mature animals.

304 Spontaneous and synchronous spawning of *H. forskali* was observed for both males and females in a delay of 2 days
 305 after the thermal stimulation. Therefore, the release of the gametes occurred mainly during the night. The amount of
 306 produced and spawned gametes was high, which is a common reproductive strategy for marine animals characterized
 307 by an external fecundation and a planktonic embryonic development. Reproductive behavior was similar to those
 308 observed in other species, thereby broodstock erected their body, below to the surface of the tank, and ejected sperms
 309 or eggs by the gonopore.

310 This preliminary study demonstrates the necessity to acquire data on the maturation cycle and spawning season of *H.*
 311 *forskali* in its natural habitat. Additional works on spawning induction and fertilization control have to be processed, to
 312 optimized hatchery procedures. Minimally invasive methods and non-lethal methods would be preferred to limit the
 313 sacrifice of broodstock. Moreover, to enhance a new and sustainable aquaculture, broodstock selection and genetic
 314 diversity will be an important point.

315 *4.2 Embryonic and larval development*

316 For this first complete description of embryonic and larval development of *H. forskali*, the larval rearing duration
 317 was 40 days (table 2, fig. 8). The embryonic development was holoblastic and the first larval stage, auricularia,
 318 hatched after 4 days and lasted more than 30 days (table 2). Pentactula and metamorphosis were obtained after 40
 319 days, this stage was longer than the other European species and Indo-pacific species (12-15 days for *H. scabra*,
 320 Ramofafia et al., 2000; 15-17 days for *Apostichopus japonica*, Ito & Kitamura, 1998; Soliman et al., 2013; Yang et al.,
 321 2015) (table 2). However, in other cultivated Echinoderms, larval life duration can be variable, as in the edible sea-
 322 urchin *Strongylocentrotus intermedius* whose duration was 20 days (Lawrence et al., 2019), in comparison with
 323 *Tripneustes depressus*, whose duration can reached 54 days (Sonnenholzner-Varas et al., 2018).

324 The breeding temperature may explain these results in part. In invertebrate hatchery, the temperature plays an
 325 important role and can decreased breeding time, for the bivalve *Crassostrea gigas*, the larval life duration decrease from
 326 27-32 days at 18°C, to 22 days at 21°C, and 18 days at 28°C (Ben Kheder et al., 2010). For comparison with temperate
 327 holothurians, breeding temperature is 24°C for *H. polii* (Rakaj et al. 2019), *H. arguinensis* (Dominguez-Godino et al.,
 328 2015) and *H. tubulosa* (Rakaj et al. 2018) (table 2). Generally, an increase of temperature reduced breeding time
 329 (Asha, 2004; Asha & Muthiah, 2005; Hamel & Mercier, 1996), therefore, larval development of temperate species is
 330 longer than tropical species (Chen & Chian, 1990; Ramofafia et al., 2003).

331 Another way to reduce larval life duration is to reduce larval density. In this present study, a high larval density has
 332 been chosen (5 to 10 larvae/mL). However, in other species, an average density of 1-2 larvae per mL is commonly

333 used (Dominguez-Godino et al., 2015; Dominguez-Godino & Gonzalez-Wangüemert, 2018; Rakaj et al. 2019). In this
334 experiment, the larvae density was high during all the auricularia stage and a high larval density can increase the larval
335 duration, the risk of pathogen development and diseases, and finally mortality (Kennedy et al., 2016). Moreover, the
336 high density decrease the food availability (Battaglione, 1999; Ramofafia et al., 2003).

337 The food sequencing and the food availability, from the first feeding larval stage, auricularia, to the non-feeding
338 stage, doliolaria, are crucial points which have consequences on duration, shape, and development of larvae (Morgan,
339 2009; Morgan, 2001; Knauer, 2011; Militz et al., 2018) and metamorphosis (Ito & Kitamura, 1997; Yang et al., 2015).
340 The phytoplankton species *Chaetoceros muelleri* and *Isochrysis galbana* are commonly used in hatchery and for
341 holothurians breeding (Hu et al., 2010; Hu et al., 2013; Mazlan & Hashim, 2015; Morgan, 2001; Rakaj et al., 2018).
342 Feeding larvae with *C. muelleri* can increase growth, survival and metamorphosis (Knauer, 2011). The use of
343 microalgae concentrates can be explored to diversify food (Duy et al., 2016; Hair et al., 2011).

344 Additional experiments will be performed to monitor survival, in order to measure zootechnical efficiency and to
345 optimize protocols.

346
347
348 **Fig. 8.** Rearing time from embryonic to the benthic larval stage pentactula in different species of sea-cucumbers. In blue: embryonic
349 stages; in light grey: auricularia stage; in green: doliolaria stage; in dark grey: pentactula (sources in table 2).

350
351
352 **Table 2.** Comparison of embryonic and larval development: rearing time, size and temperature of cultivated sea-
353 cucumbers in aquaculture.

354 355 4.3 Metamorphosis and juveniles growth

356 Metamorphosis represents a critical point in hatchery, with mortality associated. Succeed the metamorphosis stage
357 depends on parameters such as water quality, substrate, settlement material, food, hydrology, or light intensity
358 (Altaramino et al., 2017; Battaglione et al., 1999; Ramofafia et al., 2000; Gunay et al., 2015; Indriana et al., 2017; Ito &
359 Kitamura, 1997; Mercier et al., 2000) Growth and feeding methods of sea cucumbers are well-known for cultivated
360 species, but remains elusive for this species (Navarro et al., 2013; Robert et al., 2000; Uthicke, 1999). Metamorphosis
361 and settlement were effective, which represent a technical challenge. For *H. forskali*, the use of Plexiglas plates
362 covered with a microalgae fouling was successful. This type of support is common in aquaculture and is used for
363 holothurians settlement (Ito & Kitamura 1997; Morgan, 2001). An additional work on fouling will have to be done, on
364 periphitic diatoms, to optimize settlement rate and to homogenize juvenile growth (Ito & Kitamura 1997; Morgan,
365 2001), on substrate, on density and on the moment to transfer the pentactula larvae in the settlement tanks (Battaglione
366 et al., 1999). Because of its efficiency in shellfish hatchery, settlement on fine crushed shell chips could be explored.
367 Juveniles have been observed only after 60 days for this first rearing of *H. forskali*. The mean juvenile size of *H.*
368 *forskali* was 0.8 cm after 120 days and more than 4 cm after 300 days (fig.7, table 2). In the first 200 days, the juvenile
369 growth followed a polynomial equation ($y = 0,0004x^2 - 0,0022x + 1,3443$ with $R^2 = 0.9672$), described in other species
370 such as *Isostichopus fuscus* (Mercier et al., 2005). The growth rate of approximately 0.1 mm per day (fig. 7), lower
371 than the tropical cultivated species *Stichopus horrens* (0,6mm per day, Hu et al., 2013) and 0.2-0.3 mm per day after
372 60 days of culture for *H. leucospilota* (Huang et al., 2018). These growth values were lower than commercialized
373 species but similar to temperate species (table 2).

374 5. Conclusion

375
376 Taking into account over fishing of sea cucumbers in many places such as Indo-Pacific, Mediterranean regions and
377 in the Overseas Collectivity of Saint-Pierre-et-Miquelon, European species are a new target for the Asian Market.
378 Moreover, sea cucumber play an important ecological role in marine benthic ecosystems by taking part in bioturbation
379 process and nutrient recycling. *H. forskali* presents an interesting candidate as deposit feeder in integrated multi-
380 trophic aquaculture, and thus offering many opportunities to develop a sustainable aquaculture. In this context, the
381 development of aquaculture is in fact a guarantor for the sustainable management of a new fisheries resource.

382 This first description of *H. forskali* embryonic, larval development and juvenile growth aimed to enhance a new
383 aquaculture to promote diversification of production and potential export market.

384 Even if this work was carried out in a lab-scale, these preliminary results are very encouraging for the domestication
385 of this species, and 5 cm long juveniles have been produced after 250 days of breeding. This experiment is promising
386 and further research is needed to optimized zootechnical procedures and then to create a new innovative and profitable
387 aquaculture.

6. Acknowledgement and funding information

389 This work was funded by European maritime and fisheries Fund in France (HOLOFARM project, FEAMP -
390 Innovative Aquaculture) and the Brittany region (BioHol'eau project). H el ene Laguerre was supported by a "Quimper-
391 Bretagne Occidentale" grant for PhD thesis. Thanks to Morgane Nedelec and Julien Delaporte-Blanc for zootechnical
392 maintenance, Yannick Fleury for work supervising and Camille Jegou for sea-cucumbers sampling by scuba-diving.

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395 7. Authors' contributions

396 HL designed the aquaculture experiments and analysed data. HL wrote the first draft of this manuscript and PLC
397 reviewed it. All authors read and approved the final manuscript.

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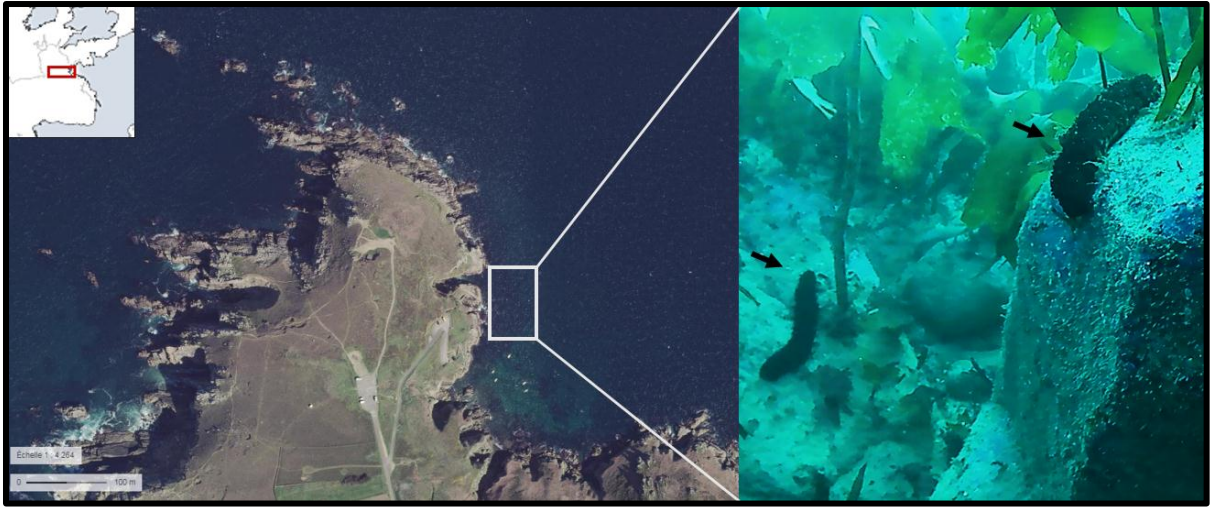
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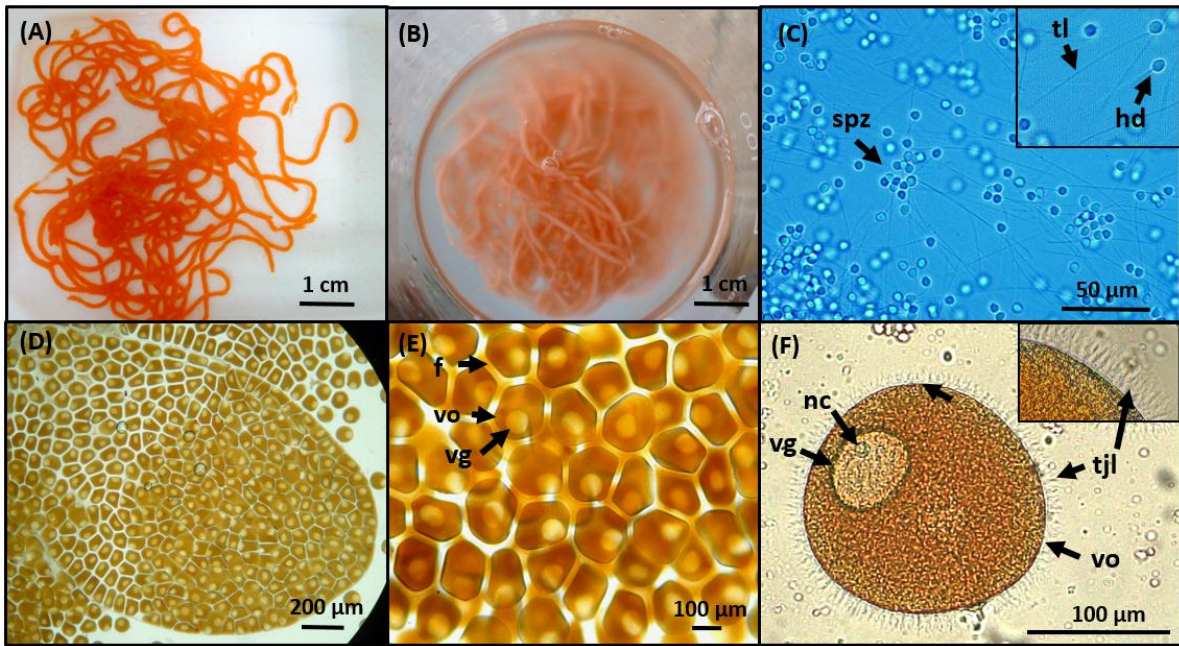
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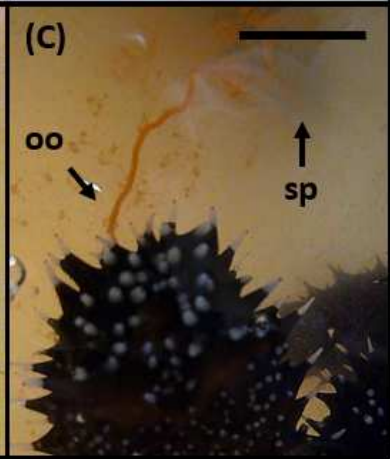
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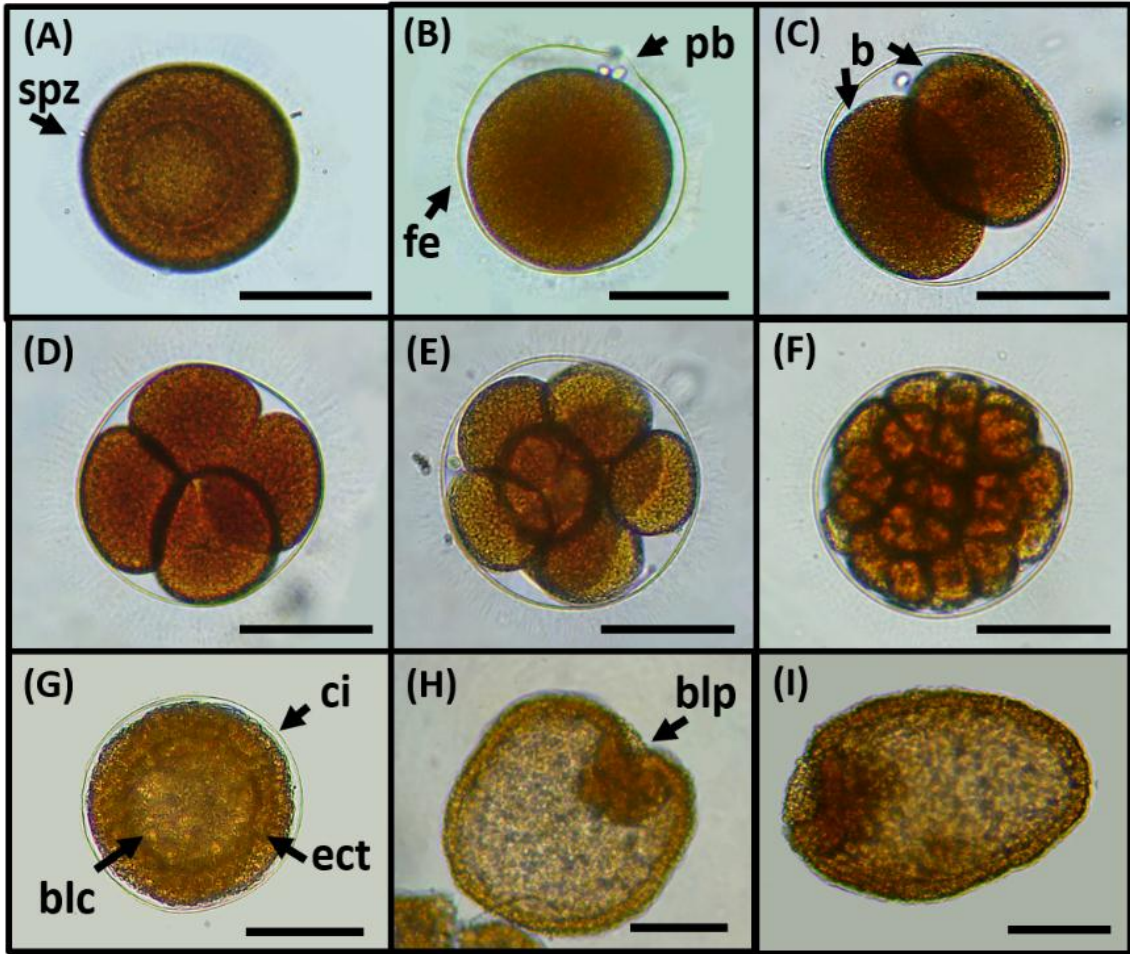
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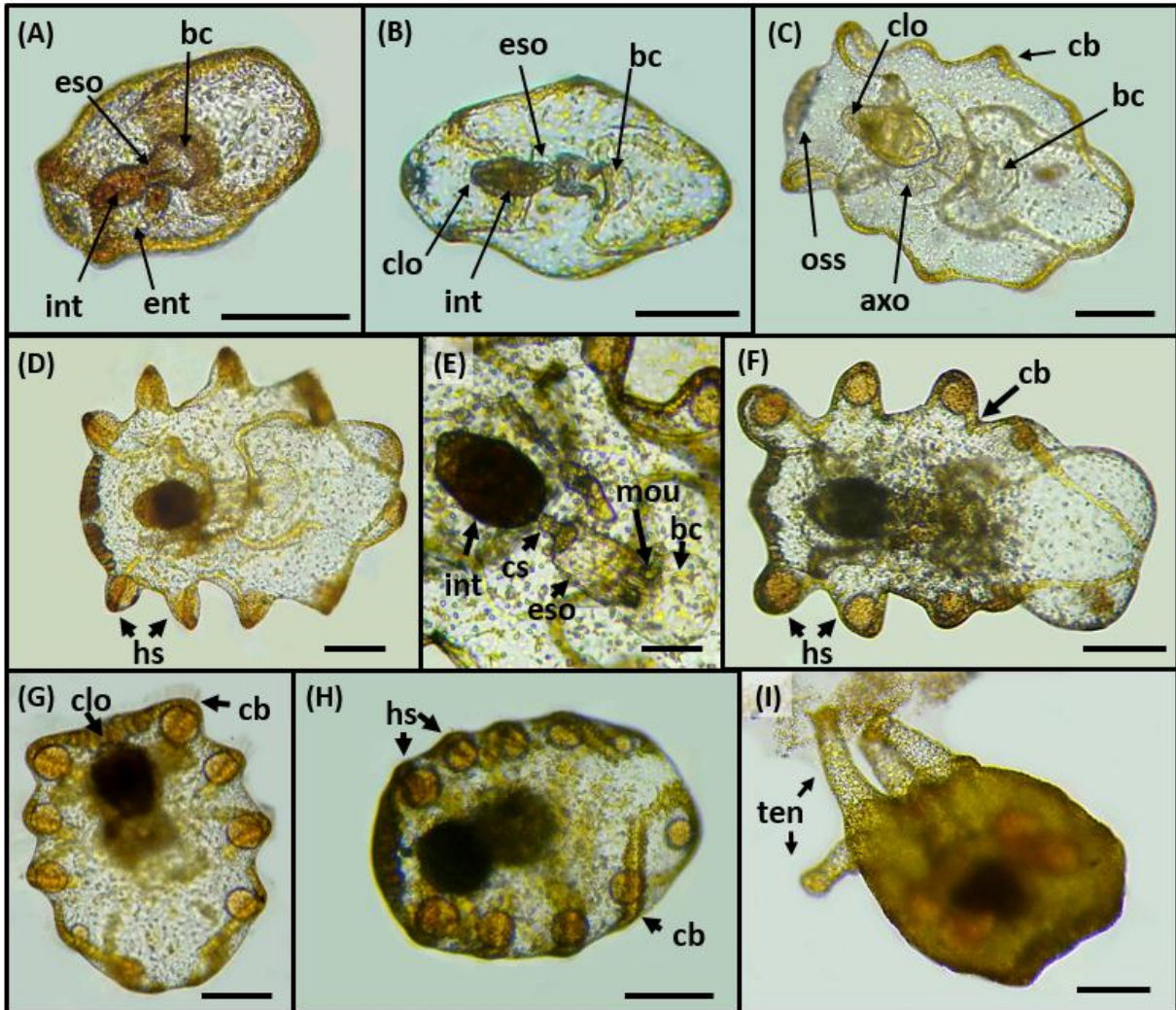
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Fig. 5. Larval development of *H. forskali* at 17°C. A: newly hatched auricularia; intestine (int), buccal cavity (bc), esophagus (eso) and enterocoel (ent). B: early auricularia; cloaca (clo). C: Mid auricularia; ossicle (oss), axohydrocoel (axo), ciliary band (cb). D-F: Late auricularia; hyaline sphere (hs), mouth (mou), cardiac sphincter (cs). G: Early doliolaria. H: Doliolaria. I: Pentactula stage; tentacles (ten). Scale bars = 200 μm.

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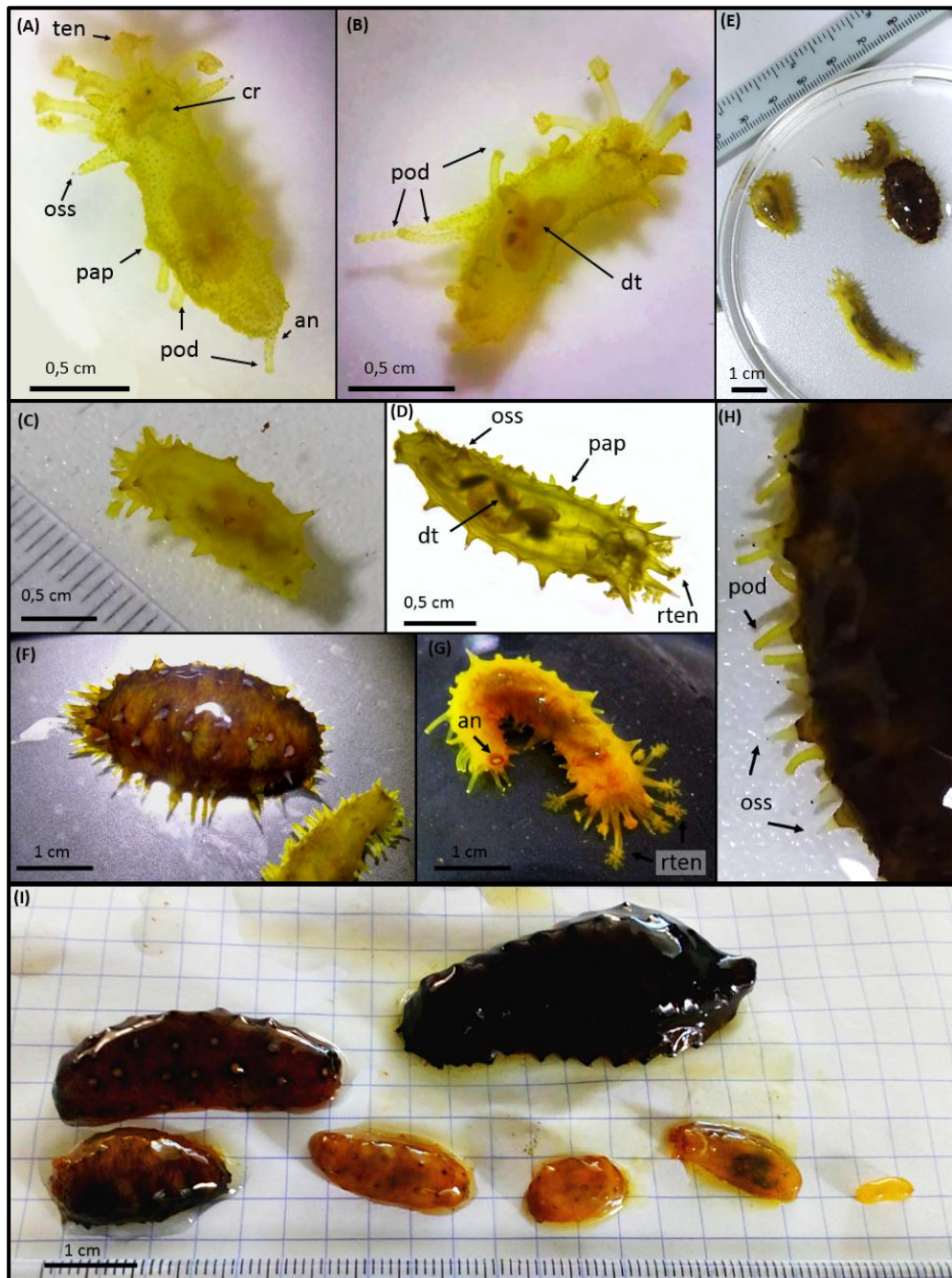


Fig. 6. Juveniles of *H. forskali*. A-B: 120-day juvenile; A: dorsal view; B: lateral view; tentacle (ten), podia (pod), calcareous ring (cr), ossicle (oss), papillae (pap), anus (an). C-D: 160-day juvenile; digestive tract (dt), ramified tentacle (rten). E-H: 250-day juveniles. G: zoom on juvenile dermis. I: 300-day juveniles.

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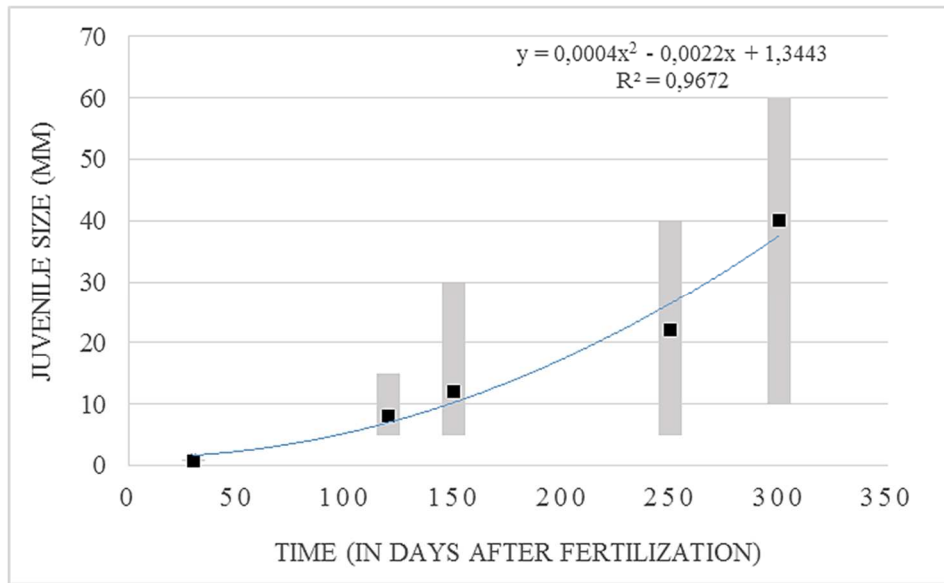
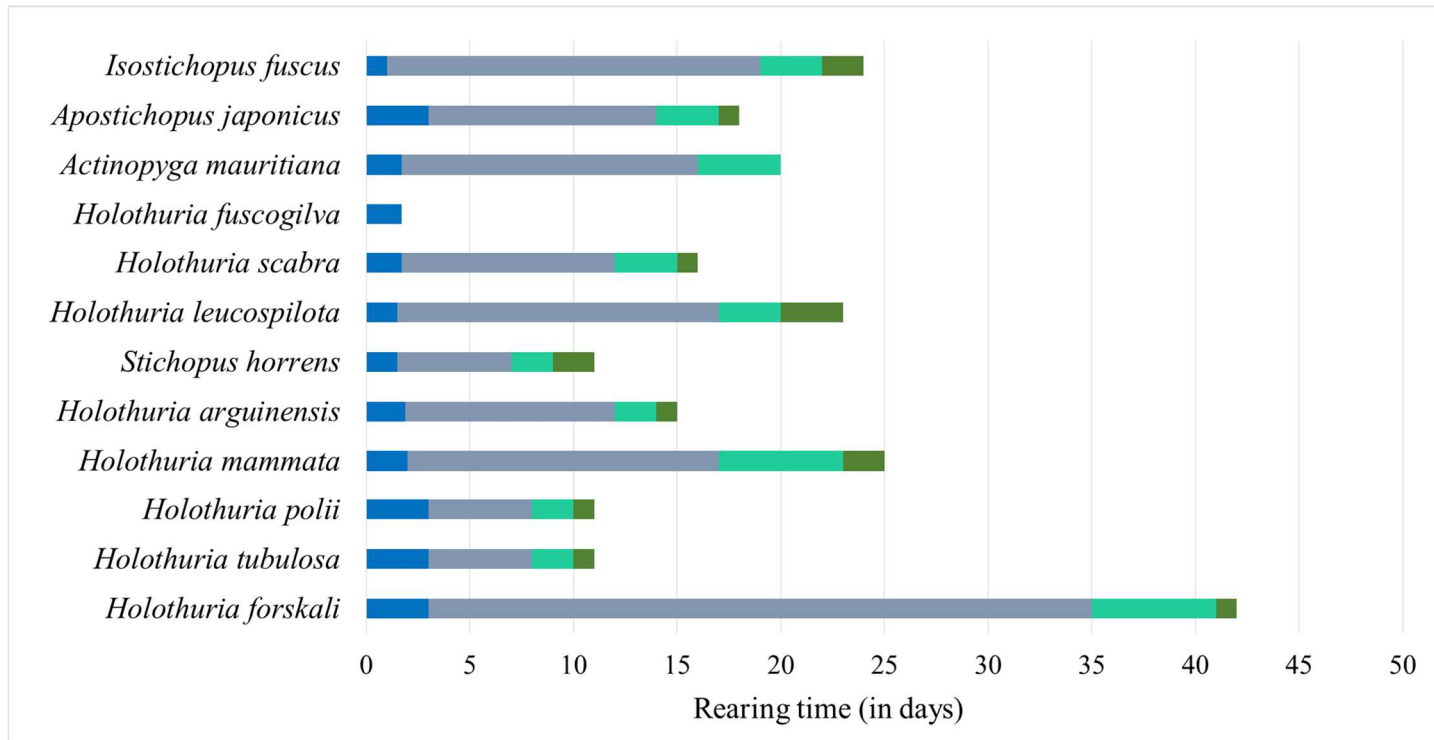


Fig. 7. Average growth of the juveniles *H. forskali*. Grey bars represented minimum and maximum sizes, the black square the mean size and the blue line the regression line with equation and R².

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Fig. 8. Rearing time from embryonic to the benthic larval stage pentactula in different species of sea-cucumbers. In blue: embryonic stages; in light grey: auricularia stage; in green: doliolaria stage; in dark grey: pentactula (sources in

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Table 1. Embryonic and larval development and size (mean \pm SD; N > 15; *N = 5; size range and mean in μm) of *H. forskali* at 17°C. Time is represented in weeks (w), days (d), hours (hr) and minutes (min), time after fertilization (AF).

Embryonic and larval stage	Size range	Mean \pm SD	Time AF
Unfertilized oocyte	[160-175]	165.46 \pm 4.29	-
Fertilized egg	[180-190]	189.07 \pm 3.63	-
2 cells egg	[185-195]	189.00 \pm 2.79	2 hr
4 cells egg	[185-200]	190.37 \pm 3.12	4 hr
8 cells egg	[185-200]	195.00 \pm 4.77	5 hr
16 - 32 cells egg*	[190-205]	195.00 \pm 4.08	7 hr
Rotary blastula	[190-210]	193.33 \pm 7.99	24 hr
Early gastrula	[210-270]	242.50 \pm 8.29	36 hr
Late gastrula	[270-310]	296.67 \pm 9.43	48 hr
Early auricularia	[300-700]	639.87 \pm 40.93	4 -6 d
Mid auricularia	[700-900]	822.74 \pm 58.30	7-25 d
Late auricularia	[900-1450]	1060 \pm 138.83	25-35 d
Doliolaria*	[700-850]	772.33 \pm 48.61	36 d
Pentactula*	[700-850]	-	42 d

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Table 2. Comparison of embryonic and larval development for cultivated sea-cucumbers in aquaculture: rearing time, size and breeding temperature and distribution area.

Species	Fertilized egg size (μm)	Newly-hatched auricularia - in time AF (days or hours)	Auricularia size range (μm)	Pentactula stage in time AF (days)	Breeding temperature ($^{\circ}\text{C}$)	Juvenile size after 90-120 days AF (mm)	Origine	References
<i>Holothuria forskali</i>	189,07 \pm 3,63	4 d	300-1450	42	17-18	8	NE Atlantic, Mediterranean - temperate waters	This study
<i>Holothuria tubulosa</i>	172,1 \pm 1,7	3 d	430-800	26	24	8,7	NE Atlantic, Mediterranean - temperate waters	Rakaj et al., 2018
<i>Holothuria mammata</i>	167,17 \pm 8,29	2 d	350-630	19-20	25-38	mortality	NE & E Atlantic, E mediterranean - temperate waters	Dominguez-Godino & Gonzalez-Wanguemert, 2018
<i>Holothuria polii</i>	247,46 \pm 15,48	3 d	300-750	9-10	24	21,0 \pm 8,2	Mediterranean - temperate waters	Rakaj et al., 2019
<i>Holothuria arguinensis</i>	171,66 \pm 5,21	45 hr	500-920	13-14	27-28	-	NE & E Atlantic, E mediterranean - temperate waters	Dominguez-Godino et al., 2015
<i>Stichopus horrens</i>	120,60 \pm 11,53	45 hr	350-1200	19-27	25-27	18-40	Indo-Pacific, Red Sea, Australia - warm waters	Hu et al., 2010; Hu et al., 2013
<i>Holothuria leucospilota</i>	140-145	36 hr	300-1500	20-23	29-33	40-70	Indo-Pacific - warm waters	Huang et al., 2018
<i>Holothuria scabra</i>	154,4 \pm 2,9	40-70 hr	300-890	12-15	25-27	30	Indo-Pacific - warm waters	Ramofafia et al., 2000; Ramofafia et al., 2003; Yan et al. 2012; Knauer 2011; Battaglione et al., 1999; Altamirano et al., 2017; Kumara et al., 2013; Mazlan & Hashim, 2015
<i>Holothuria fuscogilva</i>	151,7 \pm 5,2	40-70 hr	420-730	mortality	25-27	mortality	Indo-Pacific - warm waters	Ramofafia et al., 2000; Ramofafia et al., 2003
<i>Actinopyga mauritiana</i>	109,9 \pm 0,99	40-70 hr	300-740	mortality	25-27	mortality	Indian Ocean, Red Sea - warm waters	Ramofafia et al., 2000; Ramofafia et al., 2003
<i>Apostichopus japonicus</i>	150-200	36 hr	500-1100	15-17	17-21	> 10-20	SE Asia - temperate waters	Yang et al., 2015; Soliman et al., 2013; Ito and Kitamura, 1997
<i>Isostichopus fuscus</i>	120	1-2 d	540-1300	21-26	22-29	80	E Pacific - temperate waters	Mercier et al., 2005
<i>Athyonidium chilensis</i>	360 \pm 16	-	-	7	13	1,4	Chile, Peru - temperate waters	Guisado et al., 2012

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