HAL
archives-ouvertes.fr

Prophenoloxidase system, lysozyme and protease inhibitor distribution in the common cuttlefish Sepia officinalis

Charles Le Pabic, Georges Safi, Antoine Serpentini, Jean-Marc Lebel, Jean-Paul Robin, Noussithé Kouéta

▶ To cite this version:

Charles Le Pabic, Georges Safi, Antoine Serpentini, Jean-Marc Lebel, Jean-Paul Robin, et al.. Prophenoloxidase system, lysozyme and protease inhibitor distribution in the common cuttlefish Sepia officinalis. Comparative Biochemistry and Physiology - Part B: Biochemistry and Molecular Biology, Elsevier, 2014, 172-173, pp.96-104. 10.1016/j.cbpb.2014.04.009 . hal-00994223

HAL Id: hal-00994223
https://hal.archives-ouvertes.fr/hal-00994223

Submitted on 21 May 2014

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 # Prophenoloxidase system, lysozyme and protease inhibitor
2 # distribution in the common cuttlefish *Sepia officinalis*

3

4 Le Pabic Charles[a,b,c]#*, Safi Georges[a,b,c]#, Serpentini Antoine[a,b,c], Lebel Jean-Marc[a,b,c], Robin
5 Jean-Paul[a,b,c], Koueta Noussithé[a,b,c]

6 [a] Normandie Université, F-14032 Caen, France

7 [b] UMR BOREA, MNHN, UPMC, UCBN, CNRS-7028, IRD-207, IBFA Université de Caen
8 Basse-Normandie, Esplanade de la Paix, CS 14032, 14032 Caen cedex, France

9 [c] Centre de Recherches en Environnement Côtier, Université de Caen Basse-Normandie, 54
10 rue du Docteur Charcot, 14530 Luc-sur-Mer, France

11

12 # These authors contributed equally to the study

13

14 *Corresponding author: Charles Le Pabic
15 UMR BOREA, MNHN, UPMC, UCBN, CNRS-7028, IRD-207,
16 IBFA Université de Caen Basse-Normandie, Esplanade de la
17 Paix, CS 14032, 14032 Caen cedex, France
18 Tel.: (+33) 231 565 102
19 Fax: (+33) 231 565 346
20 e-mail : charles.lepabic@gmx.fr
21

22 ## Abstract

23 The immune system of cephalopods remains poorly understood. The aim of this study
24 was to determine the specific activity of immune enzymes in epithelial barriers, circulatory
25 and digestive systems of the common cuttlefish *Sepia officinalis*. Three enzyme groups with
26 putative functions in immunity were investigated: phenoloxidases (POs), lysozymes and
27 protease inhibitors (PIs). Consistent with role in immunity, highest PO activities were found
28 in the integument as well as the respiratory and circulatory organs under zymogenic (proPO)
29 and active form. Surprisingly, high PO activities were also found in the digestive gland and its
30 appendages. Similarly, high lysozyme activities were detected in the integument and

31 circulatory organs, but also in the posterior salivary glands, highlighting the implication of
32 this antibacterial enzyme group in most tissues exposed to the environment but also within the
33 circulatory system. Albeit highest in digestive organs, the ubiquitous detection of PI activity
34 in assayed compartments suggests immune function(s) in a wide range of tissues. Our study
35 reports proPO/PO, lysozyme and PI distributions in *S. officinalis* body compartments for the
36 first time, and thus provides the fundamental basis for a better understanding of the humoral
37 immune system in cephalopods as well as invertebrates.

38 **Keywords:** cephalopod, immune system, lysozymes, prophenoloxidase system, protease
39 inhibitors, *Sepia officinalis*

40 **1. Introduction**

41 Most aquatic organisms inhabit environments rich in bacteria and other microorganisms.
42 Unlike air, water functions as a medium for both transport and growth of microbes (Gomez et
43 al., 2013; Hansen and Olafsen, 1999; McFall-Ngai et al., 2010). Thus a critical function of the
44 immune system of aquatic organisms is to provide a protection against this constant
45 pathogenic threat (Iwanaga and Lee, 2005). What adaptations of the immune system allow
46 aquatic species to thrive in these conditions? Unlike vertebrates, invertebrates rely on innate
47 immunological mechanisms alone as defense against pathogens (Loker et al., 2004). Cell-
48 mediated defense mechanisms are mainly carried out by hemocytes, which behave like
49 macrophages (Heath-Heckman and McFall-Ngai, 2011), while humoral factors take part in
50 various functions such as pathogen recognition, signaling pathway activation, and invader[1]

---

[1]**Footnote 1:** *Abbreviations:* APO: activated phenoloxidase; BAPNA: Nα-benzoyl-L-arginine 4-nitroanilide hydrochloride; BH: branchial hearts; BHA: branchial heart appendages; BSA: bovin serum albumin; Cu: copper; DG: digestive gland; DGA: digestive gland appendages; DMSO: dimethyl sulfoxide; HEW: hen egg white; Hcy: hemocyanin; L-DOPA: 3,4-Dihydroxy-L-phenylalanine; PI: protease inhibitor; PO: phenoloxidase; proPO:

51 elimination (Wang et al., 2013). Among them, we chose to focus on (1) one of the most
52 effective signaling pathway of invertebrates – the melanization cascade, (2) one well-known
53 hydrolytic enzyme group involved in pathogen elimination – the lysozymes, and (3)
54 components of the immune proteolytic cascade, the protease inhibitors (PIs) (Amparyup et al.,
55 2013; Cerenius et al., 2008; Fiołka et al., 2012; Herreweghe and Michiels, 2012; Rowley and
56 Powell, 2007; Wang et al., 2013; Xue et al., 2009).

57 While a major immune mechanism among many invertebrate taxa, melanization remains
58 understudied in mollusks. It is involved in (1) non-self recognition, (2) production of toxic
59 compounds against pathogens, (3) wound healing and (4) cellular-defense factor synthesis
60 (e.g. Cerenius et al., 2008; Luna-Acosta et al., 2010; Siddiqui et al., 2006). Phenoloxidases
61 (POs), a family of copper (Cu) proteins catalyse the rate-limiting step in melanin production:
62 oxidation or hydroxylization of phenols into quinones. Importantly, POs are synthetized as
63 zymogenic form called prophenoloxidases (proPO) and activated by serine protease cleavage
64 (Amparyup et al., 2013; Cerenius and Söderhäll, 2004; Masuda et al., 2012). Because of their
65 immune functions highest PO levels are usually found in association with epithelial barriers,
66 respiratory and circulatory systems in arthropods and bivalves (Asano and Ashida, 2001;
67 Franssens et al., 2008; Luna-Acosta et al., 2011a; Masuda et al., 2012; Zhou et al., 2012).

68 Lysozymes cleave the 1,4-β-glycosidic linkage between N-acetylglucosamine and N-
69 acetylmuramic acid of bacteria cell walls in order to lyse the cell – a process used in both
70 immune defense and gastric digestion (Herreweghe and Michiels, 2012). Apart from this
71 antimicrobial property, lysozymes interact with immune system compounds (e.g. complement
72 pathway, lectins, proPO) to modulate or enhance humoral immune response (Goto et al.,

---

prophenoloxidase; PSG: posterior salivary glands; SE: standard error; SH: systemic heart; Stc: stomach; TI: trypsin inhibition; WB: white bodies

73 2007; Herreweghe and Michiels, 2012; Park et al., 2007; Rao et al., 2010; Wang and Zhang,
74 2010). Their chitinase activity is also used to ward off fungal infection (Herreweghe and
75 Michiels, 2012). Consistent with these properties they are mainly associated with the
76 epithelial barriers, respiratory and circulatory systems of numerous aquatic organisms such as
77 bivalves and fish, and in some cases digestive tracts of bivalves because of their use of
78 bacteria as food (Herreweghe and Michiels, 2012; Saurabh and Sahoo, 2008).

79 Finally, PIs aid in the defense of various organisms by regulating or inhibiting bacterial
80 protease activities through interaction with their reaction sites or entrapment. PIs also play a
81 central role in the regulation of a wide variety of immune processes including (1) hemolymph
82 coagulation, (2) proPO activation and (3) synthesis of cytokines and antimicrobial peptides
83 (Xue et al., 2009). However, PIs also take part in other processes such as digestion, where
84 protease regulation is necessary and are consequently not concentrated in tissues with immune
85 functions.

86 Cephalopods are a highly derived group in the molluscan clade, with a complex nervous
87 system allowing elaborate body patterning and behaviour, a deeply modified body plan
88 organization, and highly diverse modes of life (Bassaglia et al., 2013; Hanlon and Messenger,
89 1988). However little is known about their immune system (Castellanos-Martínez and Gestal,
90 2013; Ford, 1992). Furthermore, cephalopods possess anatomical peculiarities within
91 mollusks such as a closed circulatory system with a central systemic heart (SH) and two
92 branchial heart (BH) complexes (Schipp, 1987), as well as clearly identified hematopoietic
93 organs – the white bodies (WB) (Claes, 1996), suggesting immune pathway modifications.
94 Yet, immune involvement of POs has never been studied in cephalopods, only one study
95 reported lysozyme repartition in the octopod *Eledone cirrhosa* (Malham et al. 1998), and PI
96 activity was mostly described in the plasma (Armstrong, 1992; Thøgersen et al., 1992;

97 Vanhoorelbeke et al., 1994), and the digestive gland of several species (Ishikawa et al., 1966;
98 Kishimura et al., 2010, 2001; Sof'ina et al., 1988).

99 Based on previously described enzyme repartitions and roles, we hypothesized that (1)
100 higher proPO/PO- and lysozyme-activities would be found in the circulatory system and
101 tissues directly exposed to the outer environment in *Sepia officinalis*: plasma, BH and their
102 appendages (BHA), SH, WB, integument, mantle and gill, and (2) that PIs would be
103 ubiquitous in *S. officinalis* compartments because of the general need to regulate proteases.

104 Here, we report the distribution of proPO/PO, lysozymes and PIs in 13 body
105 compartments selected for their functions in circulation, respiration, immunity, digestion or as
106 physical barriers in adult common cuttlefish: respiratory and circulatory compartments (gill,
107 plasma, SH, BH, BHA, and WB), digestive organs (posterior salivary glands (PSG), stomach
108 (Stc), cecum, digestive gland (DG) and its appendages (DGA)), and integument and mantle,
109 as first epithelial barrier and underlying muscle tissue, respectively. Higher activated PO
110 (APO)- and lysozyme-activities were mainly found in the integument, circulatory and
111 respiratory organs consistent with a role in immunity. In addition, we found high PO-
112 activities in the DG, potentially highlighting its role(s) in protection of the digestive tract
113 against infections and/or hemocyanin (Hcy) metabolism. Lastly, higher PI-activities were
114 mostly found in digestive system organs despite their presupposed ubiquitous repartition.

115 **2. Material and methods**

116 *2.1. Animals and tissue samples*

117 Ten adult common cuttlefish *S. officinalis* (mean ± standard deviation; weight = 1.03 ±
118 0.38 kg; dorsal mantle length = 21.3 ± 3.5 cm) were obtained from traps deployed along the
119 Calvados coast (Basse-Normandie, France) during summer 2012. Prior to experimentation,

120 the animals were maintained in 4500-liter tanks in an open seawater circuit and starved for 24
121 h at 15°C at the Centre de Recherches en Environnement Côtier (C.R.E.C., Luc-sur-Mer,
122 Basse-Normandie, France).

123 In order to study basal enzymatic activities in cuttlefish tissue, we used animals without
124 visible wounds, with normal swimming behavior and predatory behavior display upon prey
125 presentation. We also carefully visually checked for the absence of macroscopic parasites in
126 animals and organs sampled. Following ethical procedures (Directive 2010/63/EU), cuttlefish
127 were anesthetized as described by Andrews et al. (2013) through placement for 10 min in
128 seawater containing 2% ethanol. Five ml hemolymph was then withdrawn from anterior
129 mantle vein (King et al., 2005) using syringe with 18-gauge needle and kept in ice, and
130 animals killed by rapid decapitation. Digestive gland, DGA, PSG, Stc, cecum, WB, SH, gill,
131 BHs and BHA were then harvested and placed on ice. In addition, pieces of mantle and
132 integument (with associated mucus) were sampled (Fig. S1). At the end of the dissection,
133 tissues were rinsed in cold extraction buffers and kept at -80°C until enzyme extraction.
134 Hemolymph samples were centrifugated at 500 g to separate plasma and hemocyte fractions,
135 and cell-free plasma was stored at -80°C until analysis.

136 *2.2. Chemicals*

137 Aprotinin, Nα-benzoyl-L-arginine 4-nitroanilide hydrochloride (BAPNA), bovin
138 serum albumin (BSA), Bradford reagent, calcium chloride ($CaCl_2$), citric acid ($C_6H_8O_7$),
139 dimethyl sulfoxide (DMSO), hen egg white (HEW) lysozyme, 3,4-dihydroxy-L-
140 phenylalanine (L-DOPA), magnesium chloride ($MgCl_2$), freeze-dried *Micrococcus*
141 *lysodeikticus*, Protease Inhibitor Cocktail, sodium chloride (NaCl), sodium phosphate dibasic
142 dihydrate ($Na_2HPO_4{\cdot}2H_2O$), trizma base, trizma hydrochloride (Tris-HCl), tropolone and
143 trypsin TPCK (N-tosyl-L-phenylalanyl chloromethyl ketone) were obtained from Sigma-

144 Aldrich (France). Halt Protease Inhibitor Cocktail, EDTA-Free (100X) was obtained from
145 Thermo Fisher Scientific (Waltham, USA).

146 *2.3. Enzyme extraction*

147 Tissue samples were weighed before to be ground in liquid nitrogen. Once a fine
148 powder was obtained, the sample was homogenised in a known amount (10 ml to 1 g) of cold
149 Tris buffer pH 8 (10 mM Tris-HCl and 150 mM NaCl) for lysozyme and PI assays (Safi,
150 2013) or Tris buffer pH 7 (0.1 M Tris-HCl, 0.45 M NaCl, 26 mM $MgCl_2$ and 10 mM $CaCl_2$)
151 for PO assay (Luna-Acosta, 2010). The mixture was homogenized, stored at 4°C for 1 h, and
152 then centrifuged for 10 min at 15,000 g and 4°C. The resulting supernatant containing Tris
153 soluble proteins was collected for enzymatic studies.

154 *2.4. Biochemical analysis*

155 *2.4.1. Protein assays*

156 All activities were expressed in relation to protein concentration measured according to
157 the Bradford method (1976) using BSA as standard.

158 *2.4.2. PO assays*

159 In order to partly discriminate PO synthesis and activation site, we took care to avoid
160 unwanted activation of proPO during each step of experiment. PO-like activity was measured
161 spectrophotometrically by recording the formation of *o*-quinones, as described by Luna-
162 Acosta (2010) with slight modifications to distinguish artificially activated PO (APO)
163 (corresponding to PO-like activity resulting from zymogenic PO (proPO) activation plus
164 already 'active' form) and *in vivo* 'active' PO form. PO assays were conducted in triplicate in
165 96-well flat bottom plates (BD, USA). L-DOPA was used as substrate, at a final concentration

166 of 10 mM (Luna-Acosta, 2010), and prepared extemporaneously in Tris buffer pH 7 described
167 above (section 2.3.). Tropolone (10 mM) and trypsin TPCK (1 g l^{-1}) were used respectively as
168 PO inhibitor and elicitor as described by Lacoue-Labarthe et al. (2009) on *S. officinalis*
169 embryo. To avoid uncontrolled proPO activation by tissue endogenous proteases, several
170 wide spectrum PIs were tested: aprotinin (1 g l^{-1}), Protease Inhibitor Cocktail (D/100) and
171 Halt Protease Inhibitor Cocktail, EDTA-Free (1X). For each sample, non-enzymatic sample
172 autoxidation, 'basal', 'inhibited' and 'activated' PO-like activities were measured. For non-
173 enzymatic sample autoxidation, 10 µl of sample was mixed with Tris buffer pH 7. For 'basal'
174 PO-like activity, 10 µl of sample was firstly mixed during 10 min with 1.4 µl PI (100X),
175 followed by adapted volume of Tris buffer pH 7 and 80 µl L-DOPA. Similarly, for inhibited
176 or APO-like activity, 10 µl of sample was mixed with 10 µl of tropolone (140 mM) or trypsin
177 TPCK (14 g l^{-1}), Tris buffer pH 7 and 80 µl L-DOPA. Each measurement was systematically
178 controlled by replacing sample by buffer, always in a final reaction volume of 140 µl.
179 Immediately after L-DOPA addition, PO-like activities were monitored at 25°C for 5 h using
180 Mithras LB 940 luminometer (Berthold, Thoiry, France) at 490 nm (Luna-Acosta, 2010).
181 When an inhibited PO-like activity was measured, this value was subtracted from APO and
182 PO-like activities. Tropolone, with its copper chelator and peroxidase substrate properties,
183 ensured that PO-like activity alone was detected (and not peroxidase). Results were also
184 systematically corrected for non-enzymatic autoxidation of the substrate and were expressed
185 in enzyme unit (1 U) per mg of total protein. One U corresponded to an increase of 0.001 in
186 the absorbance per min at 25°C (Thomas-Guyon et al., 2009).

187 Preliminary assays showed similar effects on PO-like activity with aprotinin (1 g l^{-1}),
188 Protease Inhibitor Cocktail (D/100) and Halt Protease Inhibitor Cocktail - EDTA-Free (1X),
189 with concentrations inhibiting 1 g l^{-1} elicitor trypsin TPCK, which is much higher than
190 maximal tissue intrinsic serine protease concentrations found in these compartments (not

191 shown). Consequently, Halt Protease Inhibitor Cocktail - EDTA-Free was used in our study.
192 The use of a PI Cocktail to avoid unwanted *in vitro* proPO activation by tissue endogenous
193 proteases allowed to distinguish PO-like activities from already activated form when
194 sampling occurred, and those from inactive zymogenic form proPO at the same moment.
195 Therefore, in addition to activity levels, PO and APO-like activities informed us about proPO
196 location and compartments where proPO activation occurs most often, i.e. compartments most
197 submitted to uncontrolled elicitors (intern or extern).

198 *2.4.3. Lysozyme assay*

199 Lysozyme-like activity was quantified according to Malham et al. (1998) with slight
200 modifications. Fifty µl of HEW lysozyme (85 µg ml^{-1} in Tris buffer pH 8 described in section
201 2.3.) standard was serially diluted and placed in triplicate in 96-well flat bottom plates (BD,
202 USA), as well as 50 µl of each sample and 50 µl of Tris buffer pH 8, as blank. One hundred
203 and fifty µl of the substrate, *M. lysodeikticus* [0.075 g/100 ml of phosphate/citrate buffer pH
204 5.8 ($Na_2HPO_4 \cdot 2H_2O$, 4.45 g/250 ml distilled H_2O; $C_6H_8O_7$, 2.1 g/100 ml distilled H_2O; NaCl,
205 0.09 g/100 ml buffer)], was then added to each well. The reductions in turbidity in the wells
206 were read on Mithras LB 940 luminometer (Berthold, Thoiry, France) at 25°C for 5 minutes
207 at 10 second intervals at 450 nm using negative kinetics. Lysozyme concentrations were
208 calculated from the standard curve (µg HEW lysozyme equivalent ml^{-1}). Final lysozyme-like
209 activity was thus expressed as µg HEW lysozyme eq. mg $protein^{-1}$.

210 *2.4.4. PI assay*

211 As described by Malham et al. (1998) and Thompson et al. (1995), PI activity was
212 measured by transferring 20 µl of sample and 10 µl of trypsin TPCK (100 µg ml^{-1} of 0.05 M
213 Tris buffer pH 8) in 96-well flat bottom plates (BD, USA), and mixed at room temperature for
214 5 minutes. In parallel, intrinsic trypsin activity was measured by replacing 10 µl of trypsin by

215 Tris buffer pH 8 described in section 2.3. A positive control was used by replacing the sample
216 with Tris buffer pH 8. Two hundred µl of BAPNA substrate solution (5.2 mg BAPNA ml^{-1}
217 DMSO in 10 ml of 0.01 M trizma base buffer pH 7.4) was added to each well and incubated
218 for 15 minutes at room temperature. Absorbance was read at 405 nm using Mithras LB 940
219 luminometer (Berthold, Thoiry, France), and PI activity was expressed as the percentage of
220 sample trypsin inhibition (TI) compared to the positive control. As most proteinaceous
221 protease inhibitors specifically inhibit proteolytic enzymes of one of four mechanistic classes
222 (i.e., aspartic proteases, cysteine proteases, metalloproteases and serine proteases) by
223 interacting with their reactive sites, this assay allowed quantifying serine PIs (Xue et al.,
224 2009). PI activity = [$O.D._{405nm}$ (sample + trypsin + S) – $O.D._{405nm}$ (sample + S)] / $O.D._{405nm}$
225 (trypsin + S) × 100. Final activity was expressed as TI % µg of $protein^{-1}$.

226 *2.5. Statistical analysis*

227 All results are given as mean ± standard error (SE) for adult organs. Residual
228 distribution was tested for normality (Shapiro test) and homogeneity of variances (Levene
229 test). In some cases, logarithmic (Log_{10}) or reciprocal transformations were used to meet the
230 underlying assumptions of normality and homogeneity of variances. For normal values, one-
231 way analysis of variance (ANOVA) were used followed by non parametric pairwise
232 permutational *t*-tests ($n < 30$). Significant differences between PO-like and APO-like
233 activities were tested for each organ with a Student's *t*-test. Statistical significance threshold
234 was set at $p < 0.05$. R software was used for statistics and graphics.

235 **3. Results and discussion**

236 *3.1. APO- and PO-like activity distribution and potential functions*

237 Based on previously described enzyme repartitions and roles, we hypothesized that
238 higher proPO/PO-activity would be found in the circulatory system and tissues directly
239 exposed to the outer environment in *S. officinalis*.

240 The highest APO-like activity was measured in the integument (12.2 ± 1.5 U mg prot^{-1}),
241 consistent with its role as first epithelial barrier (Figure 1). A role of POs in cuttlefish wound
242 healing was suggested by tissue thickening and darkening (Harms et al., 2006) similar to the
243 proPO induced sclerotization and pigmentation process of the insect cuticle (Arakane et al.,
244 2005; Pryor, 1940). Apart from their roles in immunity, POs may be involved in cuttlefish
245 body patterning by chromatophore melanogenesis although melanin presence as pigment in
246 the cephalopod integument remains controversial (see Messenger, 2001). Future studies will
247 have to determine PO implication in one or both processes in *S. officinalis* integument as
248 already shown in vertebrates (Haffner and Wieser, 1981; Mackintosh, 2001; Zanna et al.,
249 2009). It is also noteworthy that the mantle, the main body part in direct contact with the
250 integument did not present any PO activity, suggesting local proPO synthesis. Similar PO
251 repartition was recently reported in bivalve mollusks with high and low activities in mantle
252 and muscle, respectively (Luna-Acosta et al., 2011b; Zhou et al., 2012).

253 In the plasma, POs and Hcy share a structurally and functionally equivalent active site
254 (Campello et al., 2008), yet POs are synthetized as inactive zymogenic form while Hcy is not.
255 In addition, Hcy constitutes more than 90% of the total plasma protein content (D'Aniello et
256 al., 1986; Ghiretti, 1966; Mangold and Bidder, 1989). Consequently, parallel assays of APO-
257 and PO-activities allowed to distinguish between Hcy- and non-Hcy-associated PO activities,
258 as PO-activity mostly resulted from Hcy oxidation (Siddiqui et al., 2006). The plasma was
259 indeed the only compartment where PO- and APO-like activities were similar (2.6 ± 0.3 U mg

260 prot^{-1}), strongly suggesting that (1) plasma PO-activity was mostly Hcy-associated and that
261 (2) PO-activity from other compartments is mostly associated with PO enzymes. It is thus
262 interesting to note that, except for the mantle, all studied compartments presented some APO-
263 like activity, consistent with a wide role of POs in cuttlefish immunity (Figure 1). The
264 previously suggested lectin role of Hcy and the Hcy-derived PO activity found in our study,
265 as well as in other cephalopods, are consistent with recently reviewed roles of Hcy as an
266 integral component of invertebrate innate immunity and suggest a function in immune
267 response trigger (Alpuche et al., 2010; Amparyup et al., 2013; Campello et al., 2008; Coates
268 and Nairn, 2014; Rögener et al., 1985; Siddiqui et al., 2006; Wang and Wang, 2013).

269 Organs of the respiratory and circulatory systems presented similar APO-like activities
270 around 7 U mg prot^{-1} (except WB) with only PO-like activity found in BH (1.0 ± 0.3 U mg
271 prot^{-1}). Such results are consistent with PO role(s) associated with the immune system: non-
272 self recognition, antibacterial compound synthesis and production of factors stimulating
273 cellular defense (Cerenius et al., 2008; Söderhäll and Cerenius, 1998). The low PO-like
274 activity measured in BH could not be ascribed to either Hcy or POs, because of the role of BH
275 cells (i.e. rhogocytes and adhesive hemocytes) in hemolymph epuration of xenobiotics and
276 allogenic substances (Beuerlein and Schipp, 1998; Beuerlein et al., 2002), and their
277 involvement in Hcy catabolism suggested by Beuerlein et al. (1998). Finally, high APO-
278 activity with lack of 'basal' PO-like activity in BHA was consistent with the Hcy extracellular
279 storage suggested by Beuerlein et al. (2000). WB APO-like activity (2.4 ± 1.0 U mg prot^{-1})
280 suggested proPO presence in hemocytes before their release in cuttlefish plasma.

281 As expected, APO- and PO-like activities measured in the digestive system were lower
282 than in other systems, except for the DG-DGA complex (9.8 ± 1.0 and 5.5 ± 1.2 U mg prot^{-1},
283 respectively), which presented higher APO-like activities than Stc, cecum and PSG (2.0 ± 0.7,

284 1.8 ± 0.6 and 1.5 ± 0.5 U mg prot^{-1}, respectively). DGA are known to carry out 2 main roles
285 in *S. officinalis*; absorption of small molecules from digestion (Boucaud-Camou and Boucher-
286 Rodoni, 1983; Boucaud-Camou and Pequignat, 1973), and osmoregulation via salts and water
287 absorption to maintaining the internal hyperosmotic status of cephalopods (Schipp and
288 Boletzky, 1976; Wells and Wells, 1989). Since no known link exists between PO function and
289 digestion, DGA-associated proPO may reflect a role in the immune response, perhaps by
290 providing protection against pathogen exposure from oral or rectal uptake of seawater, which
291 occurs without exposure to digestive enzymes. In the case of the DG, PO-like activities were
292 previously detected in mollusk DGs but no tissue-specific function was proposed (Blaschko
293 and Hawkins, 1952; Blaschko, 1941; Luna-Acosta et al., 2011a, 2011b). In cephalopods, most
294 of reported parasite infections (i.e. coccidians of the genus *Aggregata,* cestodes, trematodes,
295 nematodes) were found in the digestive tract (reviewed in Castellanos-Martínez and Gestal,
296 2013; Hochberg, 1990). Because of (1) the high efficiency of melanization against parasites
297 (Rao et al., 2010), (2) the important secretory ability of the DG and (3) its central position in
298 the digestive tract, we propose that the DG may serve as proPO reservoir to fight this type of
299 infection. In addition, the ability of some POs (i.e. laccases) to catalyze aromatic oxidation
300 (Dodor et al., 2004; Luna-Acosta et al., 2011a) and the high PO-like activities found in the
301 DG may also be linked to the detoxification of these compounds known to be highly
302 accumulated in cephalopods (e.g. Ansari et al., 2012; Won et al., 2009; Yamada et al., 1997).
303 In contrast, high PO-like activity (5.7 ± 1.7 U mg prot $^{-1}$) reflects a potential role in Hcy Cu-
304 metabolism. Because of its high Cu content (Bustamante et al., 2006; Miramand and Bentley,
305 1992; Miramand and Guary, 1980; Schipp and Hevert, 1978), many studies suggested a DG
306 implication in Hcy metabolism in *S. officinalis* (Costa et al., 2014; Decleir et al., 1978;
307 Lemaire et al., 1977; Martoja and Marcaillou, 1993; Schipp and Hevert, 1978), as
308 demonstrated in DG relatives (i.e. hepatopancreas and midgut gland) of arthropods,

309 gastropods, and cephalopods (Burmester, 2002; Manubens et al., 2010; Ruth et al., 1996). In
310 *S. officinalis*, Cu-free Hcy synthesis takes place mainly in branchial glands (Schipp and
311 Hevert, 1978; Schipp et al., 1973), but the organ where Cu-binding takes place has not been
312 clearly determined (Decleir et al., 1976; Schipp and Hevert, 1978). Based on (1) low free
313 form Cu concentration found in the hemolymph (D'Aniello et al., 1986), (2) the association of
314 Cu with Hcy-size proteins in the DG (Bustamante et al., 2006; Rocca, 1969), and (3) the Hcy
315 exchanges taking place across the DG basal membrane (Martoja and Marcaillou, 1993), our
316 data (PO-like activity) add up to this mounting evidence that the DG may function as Cu-
317 binding site for Hcy.

318 Our results are consistent with role(s) of POs in cuttlefish immunity with high activities
319 found in circulatory system organs and integument as tissue directly exposed to environment.
320 High activities found in DG complex organs will need further investigations to better define
321 PO role(s) at this location, with potential links with detoxification and Hcy metabolism.

322 *3.2. Lysozyme distribution*

323 As with PO/proPO, we hypothesized that higher lysozyme-activities would be found in
324 the circulatory system and tissues directly exposed to the outer environment in *S. officinalis*:
325 plasma, BH and their appendages (BHA), SH, WB, integument, mantle and gill. All
326 compartment samples indicated some lysozyme-like activities, except for the DGA (Figure 2).
327 Our results support our hypothesis and highlight the importance of lysozymes in circulatory
328 system organs and epithelial barriers, but also in one organ involved in digestive processes,
329 the PSG. As with APO activity, one of the highest levels was found in the integument with
330 lower activity in the mantle (2.2 ± 0.9 and 0.9 ± 0.3 µg HEW lysozyme eq. mg protein^{-1},
331 respectively). This high level is likely linked to the constant integument exposure to high
332 numbers of opportunistic pathogens in water as described in fish skin (Ghafoori et al., 2014;

333 Hikima et al., 2001; Saurabh and Sahoo, 2008). Similarly, important lysozyme activity or
334 mRNA expression have been detected in mantle of gastropod *Haliotis discus discus* (Bathige
335 et al., 2013) and bivalve mollusks *Venerupis philippinarum* (Zhao et al., 2010), *Crassostrea*
336 *virginica* (Itoh et al., 2007) and *C. gigas* (Itoh et al., 2010). This localization is thus consistent
337 with previous descriptions in fish and bivalve mollusks and may reflect lysozyme activity in
338 neutralizing pathogens after injuries or bacterial infection.

339 In the circulatory system, lysozyme-like activity was found in SH, WB, BHA and BH
340 (1.7 ± 0.5, 1.4 ± 0.4, 1.3 ± 0.5 and 0.8 ± 0.2 µg HEW lysozyme eq. mg protein^{-1},
341 respectively), but not in the plasma (< 0.1). These results parallel lysozyme-like activities
342 found in the BH complex of the cephalopod *E. cirrhosa* (Malham et al., 1998) and the role of
343 endocytotic-active cells made up BH complex in purifying the hemolymph from allogenic
344 compounds (Beuerlein and Schipp, 1998; Beuerlein et al., 2002; Schipp and Hevert, 1981).
345 The absence of lysozyme-like activity found in the plasma supports our previous finding of
346 hemolymph lysozyme in hemocytes alone (Le Pabic et al., 2012), but contrast with those
347 found in the octopods *E. cirrhosa* and *Octopus vulgaris* (Grimaldi et al., 2013; Malham,
348 1996). The high activity found in WB – the site of hemocyte formation, is consistent with the
349 previously suggested association of mature hemocytes (80% of adult cuttlefish WB) with
350 lysozyme-like enzymes (Claes, 1996). Globally, the high lysozyme activities found in
351 cuttlefish circulatory organs suggested not only intracellular action after endocytosis but also
352 secretion in plasma as previously described in bivalves (Cheng et al., 1977, 1975). Apart from
353 its bactericidal activity, some studies highlighted the lysozyme property as modulator of the
354 immune response by interacting with compounds such as the complement pathway or lectins
355 (e.g. Park et al., 2007; Rao et al., 2010; Wang and Zhang, 2010; Wilson and Ratcliffe, 2000).
356 In order to investigate more deeply lysozyme roles in cuttlefish immunity, it will be

357 interesting to confirm such secretion in plasma and to determine its triggering parameters (e.g.
358 infection, stress).

359 Surprisingly gill activity (0.3 ± 0.2 µg HEW lysozyme eq. mg protein^{-1}) was among the
360 lowest activity found whereas it is an organ (1) constantly exposed to water and therefore
361 potential pathogens and (2) with inner folded epithelia suggesting some excretory function
362 (Schipp and Boletzky, 1975; Schipp et al., 1979, 1971). This low activity may result from the
363 healthy state of sampled cuttlefish. It could be thus interesting to follow potential increase of
364 lysozyme-like activity in cuttlefish gill following an exposure to bacterial contamination, as
365 shown in fish (Larsen et al., 2009; Mai et al., 2014) and abalone (Bathige et al., 2013).

366 Among digestive system organs, highest activity was found in the PSG (1.7 ± 0.3 µg
367 HEW lysozyme eq. mg protein^{-1}), which was significantly higher than in cecum, DG (0.4 ±
368 0.1 and 0.2 ± 0.1 µg HEW lysozyme eq. mg protein^{-1}, respectively) and DGA. Such results
369 are consistent with lytic lysosomal enzyme activities reported in the cephalopod *E. cirrhosa*
370 anterior salivary glands (Malham et al., 1998), and octopod and oegopsid squid paralarvae
371 PSG (Boucaud-Camou and Roper, 1995). PSG-associated lysozyme-like enzymes may be
372 involved in (1) venom diffusion, (2) “external” digestive processes (Boucaud-Camou and
373 Roper, 1995), (3) plasma depuration (Stuart, 1968), and/or (4) to prevent digestive duct
374 infection. This last possibility is consistent with the decreasing lysozyme-like activity found
375 between the PSG and the cecum, which may result from PSG excretions from uncompleted
376 digestion due to the short time period between cuttlefish fishing and dissection, the low
377 holding temperature (15°C), and the few secretion ability of Stc (Boucaud-Camou, 1973).
378 Moreover, due to their known chitinase property in certain invertebrates, lysozymes from
379 PSG could also contribute to shell digestion of crustaceans –the most important cuttlefish
380 meal (Goto et al., 2007; Herreweghe and Michiels, 2012).

381 *3.3. PI distribution*

382 Because of the general need to regulate proteases, we hypothesized a ubiquitous
383 distribution of PIs in *S. officinalis* compartments. Our results support this hypothesis as PI
384 activity was found in all studied compartments, albeit significant differences were found
385 (Figure 3). As previously described in the squid *Loligo vulgaris* (Tschesche and von Rücker,
386 1973), PI activity was highest in digestive system organs – DG, DGA, Stc and cecum, where
387 proteolytic enzymes (as serine proteases) play a major role in *S. officinalis* (Perrin, 2004; Balti
388 et al., 2012, 2009; Boucaud-Camou, 1974). Consistent with its role in digestive enzyme
389 synthesis (proteases)(Boucaud-Camou, 1974), highest PI activity was found in the DG (2.2 ±
390 0.2 TI % µg prot^{-1}), as previously shown in cephalopods (Ishikawa et al., 1966; Kishimura et
391 al., 2010, 2001; Sof'ina et al., 1988). PI activities found in the DGA, Stc and cecum (1.8 ±
392 0.3, 1.7 ± 0.4, 1.5 ± 0.4 TI % µg prot^{-1}) might mostly result mainly from DG enzymatic
393 excretions. Indeed, among these three organs, protease synthesis was clearly highlighted in
394 cecum epithelial cells alone, but in much lower amounts than in the DG (Boucaud-Camou,
395 1974). The absorption function of the cecum implies a prolonged contact with digestive fluids
396 enriched in DG proteases (Boucaud-Camou and Pequignat, 1973). Therefore, a need to
397 control and/or protect cecum epithelia against proteases may constitute a role for associated
398 PI-activity. Lastly, it was previously argued that DGA-associated proteolytic activity is likely
399 to result from extrinsic sources because to its function (1) as excretory route for enzymes and
400 digestive fluids between DG, Stc and cecum (Boucaud-Camou, 1974; Boucaud-Camou and
401 Boucher-Rodoni, 1983), but also (2) as main absorption site for small molecules from
402 protease rich digestive fluid (Boucaud-Camou and Pequignat, 1973). Finally, no digestive
403 enzymatic activity has been found in Stc epithelium by Boucaud-Camou (1973), but this
404 organ involved in mechanical digestion collects enzyme excretion from DG and probably
405 from PSG (Boucaud-Camou and Boucher-Rodoni, 1983). Concerning PSG, the detected

406 activity may be involved in the regulation of proteases present in the cephalopod saliva
407 (Malham et al., 1998) such as chymotrypsin, which is concentrated in this tissue (Perrin,
408 2004). However cephalopod salivary glands are also known to contain biologically active
409 amines and toxins (Boucaud-Camou and Boucher-Rodoni, 1983; Boyle and Rodhouse, 2005;
410 Fry et al., 2009; Nagai, 2012; Undheim et al., 2010), and PIs may have a synergistic effect
411 with toxins as described for proteases in *E. cirrhosa* saliva (Grisley and Boyle, 1987). This
412 suggests the presence of different PIs in this tissue than in other digestive organs.

413 PI activities were lower in remaining compartments. Similar PI activities averaging at
414 0.5 TI % µg prot^{-1} were found in all respiratory and circulatory compartments as previously
415 reported in *E. cirrhosa* (Malham et al., 1998), except in the plasma. However, a PI – α_2-
416 macroglobulin, was described as the second-most abundant protein found in the *S. officinalis*
417 plasma (Armstrong, 1992; Thøgersen et al., 1992; Vanhoorelbeke et al., 1994). α_2-
418 macroglobulin acts by surrounding a wide range of protease molecules – including trypsin, to
419 prevent enzyme-substrate reaction, but does not prevent reaction with low molecular weight
420 substrates such as the BAPNA used in our study. Therefore, the low PI activity found in our
421 plasma assays (<0.1 TI % µg prot^{-1}) did not reflect α_2-macroglobulin activity. Other studies
422 on tissues of terrestrial gastropod *Helix pomatia* and cephalopod *L. vulgaris* evidenced at least
423 two different groups of PIs. A heat- and acid-stable group (I) and a group sensitive to
424 denaturation (II) differently located in both mollusks. Whereas *H. pomatia* presented group I
425 PIs only in its external organs, almost all sampled tissues (organ of the digestive tract, gills,
426 epithelial barriers) of the squid presented PIs of this group, except sexual organs which
427 contained group II PIs in both mollusks (Tschesche and Dietl, 1972; Tschesche and von
428 Rücker, 1973). Each group was able to inhibit a wide range of serine proteases involved in
429 digestive and immune processes (trypsin, chymotrypsin, plasmin, kallikrein) with different
430 yields. These observations suggested that PIs assessed in our study belong to the same PI

431 group (I), to the exception of the plasma. Thus, while our results highlight the presence of PI
432 activity in cuttlefish respiratory and circulatory compartments, they also demonstrate the need
433 for more detailed approaches to dissect out which specific PIs are associated with individual
434 organs.

435 **Acknowledgments**

436 This work was supported by the European, Interreg IV-A CRESH and CHRONEXPO
437 projects. This study was partly conducted in the CREC (Centre de Recherche en
438 Environnement Côtier) at Luc-sur-mer (Normandie, France). We would like to thank Doctors
439 Pierre Le Pabic and Thomas Lacoue-Labarthe for advices and help in English.

440 References

441 Alpuche, J., Pereyra, A., Mendoza-Hernández, G., Agundis, C., Rosas, C., Zenteno, E., 2010.
442 Purification and partial characterization of an agglutinin from *Octopus maya* serum.
443 Comp. Biochem. Physiol. Part B Biochem. & Mol. Biol. 156, 1–5.

444 Ansari, Z.A., Desilva, C., Badesab, S., 2012. Total petroleum hydrocarbon in the tissues of
445 some commercially important fishes of the Bay of Bengal. Mar. Pollut. Bull. 64, 2564–8.

446 Amparyup, P., Charoensapsri, W., Tassanakajon, A., 2013. Prophenoloxidase system and its
447 role in shrimp immune responses against major pathogens. Fish & Shellfish Immunol.
448 34, 990–1001.

449 Andrews, P.L.R., Darmaillacq, A.-S., Dennison, N., Gleadall, I.G., Hawkins, P., Messenger,
450 J.B., Osorio, D., Smith, V.J., Smith, J.A., 2013. The identification and management of
451 pain, suffering and distress in cephalopods, including anaesthesia, analgesia and humane
452 killing. J. Exp. Mar. Bio. Ecol. 447, 46–64.

453 Arakane, Y., Muthukrishnan, S., Beeman, R.W., Kanost, M.R., Kramer, K.J., 2005. *Laccase 2*
454 is the phenoloxidase gene required for beetle cuticle tanning. Proc. Natl. Acad. Sci. U. S.
455 A. 102, 11337–11342.

456 Armstrong, P.B., 1992. Humoral immunity: α_2-macroglobulin activity in the plasma of
457 mollusks. The Veliger 35, 161–164.

458 Asano, T., Ashida, M., 2001. Cuticular pro-phenoloxidase of the silkworm, *Bombyx mori*.
459 Purification and demonstration of its transport from hemolymph. J. Biol. Chem. 276,
460 11100–11112.

461 Balti, R., Barkia, A., Bougatef, A., Ktari, N., Nasri, M., 2009. A heat-stable trypsin from the
462 hepatopancreas of the cuttlefish (*Sepia officinalis*): Purification and characterisation.
463 Food Chem. 113, 146–154.

464 Balti, R., Bougherra, F., Bougatef, A., Hayet, B.K., Nedjar-Arroume, N., Dhulster, P.,
465 Guillochon, D., Nasri, M., 2012. Chymotrypsin from the hepatopancreas of cuttlefish
466 (*Sepia officinalis*) with high activity in the hydrolysis of long chain peptide substrates:
467 Purification and biochemical characterisation. Food Chem. 130, 475–484.

468 Bassaglia, Y., Buresi, A., Franko, D., Andouche, A., Baratte, S., Bonnaud, L., 2013. *Sepia*
469 *officinalis*: A new biological model for eco-evo-devo studies. J. Exp. Mar. Bio. Ecol.
470 447, 4–13.

471 Bathige, S.D.N.K., Umasuthan, N., Whang, I., Lim, B.-S., Jung, H.-B., Lee, J., 2013.
472 Evidences for the involvement of an invertebrate goose-type lysozyme in disk abalone
473 immunity: cloning, expression analysis and antimicrobial activity. Fish & Shellfish
474 Immunol. 35, 1369–79.

475 Beuerlein, K., Löhr, S., Westermann, B., Ruth, P., Schipp, R., 2002. Components of the
476 cellular defense and detoxification system of the common cuttlefish *Sepia officinalis*
477 (Mollusca, Cephalopoda). Tissue Cell 34, 390–396.

478 Beuerlein, K., Schimmelpfennig, R., Westermann, B., Ruth, P., Schipp, R., 1998.
479 Cytobiological studies on hemocyanin metabolism in the branchial heart complex of the
480 common cuttlefish *Sepia officinalis* (Cephalopoda, Dibranchiata). Cell Tissue Res. 292,
481 587–595.

482 Beuerlein, K., Schipp, R., 1998. Cytomorphological aspects on the response of the branchial
483 heart complex of *Sepia officinalis* L. (Cephalopoda) to xenobiotics and bacterial
484 infection. Tissue Cell 30, 662–671.

485 Beuerlein, K., Westermann, B., Ruth, P., Schimmelpfennig, R., Schipp, R., 2000.
486 Hemocyanin re-uptake in the renal and branchial heart appendages of the coleoid
487 cephalopod *Sepia officinalis*. Cell Tissue Res. 301, 413–421.

488 Blaschko, H., 1941. Amine oxidase in *Sepia officinalis*. J. Physiol. 99, 364–369.

489 Blaschko, H., Hawkins, J., 1952. Observations on amine oxidase in cephalopods. J. Physiol.
490 118, 88–93.

491 Boucaud-Camou, E., 1973. Etude de l’appareil digestif de *Sepia officinalis* L. (Mollusque
492 Céphalopode). Essai d'analyse expérimentale des phénomènes digestifs. Université de
493 Caen.

494 Boucaud-Camou, E., 1974. Localisation d’activités enzymatiques impliquées dans la
495 digestion chez *Sepia officinalis* L. Arch. Zool. Expérimentale Générale 115, 5–27.

496 Boucaud-Camou, E., Boucher-Rodoni, R., 1983. Feeding and digestion in Cephalopods, in:
497 Wilbur, K., Saleudinn, A.M.S. (Eds.), The Mollusca Vol. 5 Physiology Part. 2. New
498 York and London, pp. 149–187.

499 Boucaud-Camou, E., Pequignat, E., 1973. Etude expérimentale de l'absorption digestive chez
500 *Sepia officinalis* L. forma Funct. 6, 93–112.

501 Boucaud-Camou, E., Roper, C.F.E., 1995. Digestive enzymes in paralarval cephalopods. Bull.
502 Mar. Sci. 57, 313–327.

503 Boyle, P., Rodhouse, P., 2005. Ecology and Fisheries, 1st ed. Blackwell Publishing, Ames,
504 Iowa.

505 Bradford, M.M., 1976. A rapid and sensitive method for the quantitation of microgram
506 quantities of protein utilizing the principle of protein-dye binding. Anal. Biochem. 72,
507 248–254.

508 Burmester, T., 2002. Origin and evolution of arthropod hemocyanins and related proteins. J.
509 Comp. Physiol. B Biochem. Syst. Environ. Physiol. 172, 95–107.

510 Bustamante, P., Bertrand, M., Boucaud-Camou, E., Miramand, P., 2006. Subcellular
511 distribution of Ag, Cd, Co, Cu, Fe, Mn, Pb, and Zn in the digestive gland of the common
512 cuttlefish *Sepia officinalis*. J. Shellfish Res. 25, 987–993.

513 Campello, S., Beltramini, M., Giordano, G., Di Muro, P., Marino, S.M., Bubacco, L., 2008.
514 Role of the tertiary structure in the diphenol oxidase activity of *Octopus vulgaris*
515 hemocyanin. Arch. Biochem. Biophys. 471, 159–167.

516 Castellanos-Martínez, S., Gestal, C., 2013. Pathogens and immune response of cephalopods.
517 J. Exp. Mar. Bio. Ecol. 447, 14–22.

518 Cerenius, L., Lee, B.L., Söderhäll, K., 2008. The proPO-system: pros and cons for its role in
519 invertebrate immunity. Trends Immunol. 29, 263–271.

520 Cerenius, L., Söderhäll, K., 2004. The prophenoloxidase-activating system in invertebrates.
521 Immunol. Rev. 198, 116–126.

522 Cheng, T.C., Chorney, M.J., Yoshino, T.P., 1977. Lysozyme like activity in the hemolymph
523 of *Biomphalaria glabrata* challenged with bacterial. J. Invertebr. Pathol. 29, 170–174.

524 Cheng, T.C., Rodrick, G.E., Foley, D. a, Koehler, S. a, 1975. Release of lysozyme from
525 hemolymph cells of *Mercenaria mercenaria* during phagocytosis. J. Invertebr. Pathol.
526 25, 261–5.

527 Claes, M.F., 1996. Functional morphology of the white bodies of the cephalopod mollusc
528 *Sepia officinalis*. Acta Zool. 77, 173–190.

529 Coates, C.J., Nairn, J., 2014. Diverse immune functions of hemocyanins. Dev. & Comp.
530 Immunol. 45, 43–55.

531 Costa, P.M., Rodrigo, A.P., Costa, M.H., 2014. Microstructural and histochemical advances
532 on the digestive gland of the common cuttlefish, *Sepia officinalis* L. Zoomorphology
533 133, 59–69.

534 D'Aniello, A., Strazzullo, L., D'Onofrio, G., Pischetola, M., 1986. Electrolytes and nitrogen
535 compounds of body fluids and tissues of *Octopus vulgaris* Lam. J. Comp. Physiol. B
536 156, 503–509.

537 Decleir, W., Richard, A., Lemaire, J., Wolf, G., 1976. L'hémocyanine et la glande branchiale
538 de *Sepia officinalis* L. (mollusque cephalopode). Ann. la Société R. Zool. Belgique 106,
539 133–144.

540 Decleir, W., Vlaeminck, A., Geladi, P., Van Grieken, R., 1978. Determination of protein-
541 bound copper and zinc in some organs of the cuttlefish *Sepia officinalis* L. Comp.
542 Biochem. Physiol. 60B, 347–350.

543 Dodor, D.E., Hwang, H.-M., Ekunwe, S.I.N., 2004. Oxidation of anthracene and
544 benzo[a]pyrene by immobilized laccase from *Trametes versicolor*. Enzyme Microb.
545 Technol. 35, 210–217.

546 Fiołka, M.J., Zagaja, M.P., Hułas-Stasiak, M., Wielbo, J., 2012. Activity and
547 immunodetection of lysozyme in earthworm *Dendrobaena veneta* (Annelida). J.
548 Invertebr. Pathol. 109, 83–90.

549 Ford, L.A., 1992. Host defense mechanisms of cephalopods. Annu. Rev. Fish Dis. 2, 25–41.

550 Franssens, V., Simonet, G., Breugelmans, B., Van Soest, S., Van Hoef, V., Vanden Broeck,
551 J., 2008. The role of hemocytes, serine protease inhibitors and pathogen-associated
552 patterns in prophenoloxidase activation in the desert locust, *Schistocerca gregaria*.
553 Peptides 29, 235–41.

554 Fry, B.G., Roelants, K., Norman, J. a, 2009. Tentacles of venom: toxic protein convergence in
555 the Kingdom Animalia. J. Mol. Evol. 68, 311–321.

556 Ghafoori, Z., Heidari, B., Farzadfar, F., Aghamaali, M., 2014. Variations of serum and mucus
557 lysozyme activity and total protein content in the male and female Caspian kutum
558 (*Rutilus frisii kutum*, Kamensky 1901) during reproductive period. Fish & Shellfish
559 Immunol. 37, 139–46.

560 Ghiretti, F., 1966. Molluscan hemocyanins, in: Wilburg, K.M., Young, C.M. (Eds.),
561 Physiology of Mollusca. Vol. II. Academic press, London, New York, pp. 233–248.

562 Gomez, D., Sunyer, J.O., Salinas, I., 2013. The mucosal immune system of fish: the evolution
563 of tolerating commensals while fighting pathogens. Fish & Shellfish Immunol. 35,
564 1729–39.

565 Goto, T., Abe, Y., Kakuta, Y., Takeshita, K., Imoto, T., Ueda, T., 2007. Crystal structure of
566 *Tapes japonica* Lysozyme with substrate analogue: structural basis of the catalytic
567 mechanism and manifestation of its chitinase activity accompanied by quaternary
568 structural change. J. Biol. Chem. 282, 27459–67.

569 Grimaldi, A.M., Belcari, P., Pagano, E., Cacialli, F., Locatello, L., 2013. Immune responses
570 of *Octopus vulgaris* (Mollusca: Cephalopoda) exposed to titanium dioxide nanoparticles.
571 J. Exp. Mar. Bio. Ecol. 447, 123–127.

572 Grisley, M.S., Boyle, P.R., 1987. Bioassay and proteolytic activity of digestive enzymes from
573 octopus saliva. Comp. Biochem. Physiol. Part B Comp. Biochem. 88, 1117–1123.

574 Haffner, B., Wieser, W., 1981. Environmental effects on the dopa oxidase system in the skin
575 of *Rana temporaria* and *R. esculenta*. Comp. Biochem. Physiol. Part B Comp. Biochem.
576 68, 57–63.

577 Hanlon, R.T., Messenger, J.B., 1988. Adaptive coloration in young cuttlefish (*Sepia*
578 *officinalis* L.): the morphology and development of body patterns and their relation to
579 behaviour. Philos. Trans. R. Soc. B Biol. Sci. 320, 437–487.

580 Hansen, G.H., Olafsen, J.A., 1999. Bacterial interactions in early life stages of marine cold
581 water fish. Microb. Ecol. 38, 1–26.

582 Harms, C.A., Lewbart, G.A., McAlarney, R., Christian, L.S., Geissler, K., Lemons, C., 2006.
583 Surgical excision of mycotic (*Cladosporium sp.*) granulomas from the mantle of a
584 cuttlefish (*Sepia officinalis*). J. Zoo Wildl. Med. 37, 524–30.

585 Heath-Heckman, E.A.C., McFall-Ngai, M.J., 2011. The occurrence of chitin in the hemocytes
586 of invertebrates. Zoology 114, 191–198.

587 Herreweghe, J.M. Van, Michiels, C.W., 2012. Invertebrate lysozymes: Diversity and
588 distribution, molecular mechanism and *in vivo* function. J. Biosci. 37, 327–348.

589 Hikima, J., Minagawa, S., Hirono, I., Aoki, T., 2001. Molecular cloning, expression and
590 evolution of the Japanese flounder goose-type lysozyme gene, and the lytic activity of its
591 recombinant protein. Biochim. Biophys. Acta 1520, 35–44.

592 Hochberg, F.G., 1990. Diseases of Mollusca: Cephalopoda. Diseases caused by Protistans and
593 Metazoans, in: Kinne, O. (Ed.), Diseases of Marine Animals. Introduction, Cephalopoda,
594 Annelida, Crustacea, Chaetognatha, Echinodermata, Urochordata, III. Biologische
595 Anstalt, Helgoland, Hamburg, Germany, pp. 46–202.

596 Ishikawa, S., Nakamura, K., Shudo, K., Kitabayashi, K., 1966. Studies on fish soluble I-
597 protease inhibitor in squid liver. Suisanchyo Hokkaido-ku Suisan Kenkyusho Kenkyu
598 Hokoku 31, 112–119.

599 Itoh, N., Okada, Y., Takahashi, K.G., Osada, M., 2010. Presence and characterization of
600 multiple mantle lysozymes in the Pacific oyster, *Crassostrea gigas*. Fish Shellfish
601 Immunol. 29, 126–135.

602 Itoh, N., Xue, Q., Li, Y., Cooper, R.K., La Peyre, J.F., 2007. cDNA cloning and tissue
603 expression of plasma lysozyme in the eastern oyster, *Crassostrea virginica*. Fish
604 Shellfish Immunol. 23, 957–68.

605 Iwanaga, S., Lee, B.L., 2005. Recent advances in the innate immunity of invertebrate animals.
606 J. Biochem. Mol. Biol. 38, 128–150.

607 King, A.J., Henderson, S.M., Schmidt, M.H., Cole, A.G., Adamo, S. a, 2005. Using
608 ultrasound to understand vascular and mantle contributions to venous return in the
609 cephalopod *Sepia officinalis* L. J. Exp. Biol. 208, 2071–2082.

610 Kishimura, H., Nagai, Y., Fukumorita, K., Chiba, S., Nakajima, S., Klomklao, S., Nalinanon,
611 S., Benjakul, S., Chun, B.-S., 2010. Acid- and heat-stable trypsin inhibitory peptide from
612 the viscera of japanese common squid (*Todarodes pacificus*). J. Food Biochem. 34, 748–
613 763.

614 Kishimura, H., Saeki, H., Hayashi, K., 2001. Isolation and characteristics of trypsin inhibitor
615 from the hepatopancreas of a squid (*Todarodes pacificus*). Comp. Biochem. Physiol. B.
616 Biochem. Mol. Biol. 130, 117–123.

617 Lacoue-Labarthe, T., Bustamante, P., Hörlin, E., Luna-Acosta, A., Bado-Nilles, A., Thomas-
618 Guyon, H., 2009. Phenoloxidase activation in the embryo of the common cuttlefish
619 *Sepia officinalis* and responses to the Ag and Cu exposure. Fish Shellfish Immunol. 27,
620 516–521.

621 Larsen, A.N., Solstad, T., Svineng, G., Seppola, M., Jørgensen, T.Ø., 2009. Molecular
622 characterisation of a goose-type lysozyme gene in Atlantic cod (*Gadus morhua* L.). Fish
623 Shellfish Immunol. 26, 122–32.

624 Le Pabic, C., Goux, D., Serpentini, A., Lebel, J.-M., Koueta, N., 2012. Characterization of
625 *Sepia officinalis* haemocytes, primary-culture development and enzymatic assays on
626 serum and haemocyte fractions, in: Cephalopod International Advisory Council
627 Symposium - Official Program. Florianopolis, SC, Brazil, p. 41.

628 Lemaire, J., Richard, A., Decleir, W., 1977. Le foie embryonnaire de *Sepia officinalis* L.
629 (mollusque cephalopode): 1. Organogenèse. Haliotis 6, 287–296.

630 Loker, E.S., Adema, C.M., Zhang, S.-M., Kepler, T.B., 2004. Invertebrate immune systems-
631 not homogeneous, not simple, not well understood. Immunol. Rev. 198, 10–24.

632 Luna-Acosta, A., 2010. Les phénoloxydases chez l'huître creuse *Crassostrea gigas* :
633 biomarqueurs potentiels de stress environnemental. Université de La Rochelle.

634 Luna-Acosta, A., Kanan, R., Le Floch, S., Huet, V., Pineau, P., Bustamante, P., Thomas-
635 Guyon, H., 2011a. Enhanced immunological and detoxification responses in Pacific
636 oysters, *Crassostrea gigas*, exposed to chemically dispersed oil. Water Res. 45, 4103–
637 4118.

638 Luna-Acosta, A., Rosenfeld, E., Amari, M., Fruitier-Arnaudin, I., Bustamante, P., Thomas-
639 Guyon, H., 2010. First evidence of laccase activity in the Pacific oyster *Crassostrea*
640 *gigas*. Fish & Shellfish Immunol. 28, 719–726.

641 Luna-Acosta, A., Thomas-Guyon, H., Amari, M., Rosenfeld, E., Bustamante, P., Fruitier-
642 Arnaudin, I., others, 2011b. Differential tissue distribution and specificity of
643 phenoloxidases from the Pacific oyster *Crassostrea gigas*. Comp. Biochem. Physiol. Part
644 B Biochem. & Mol. Biol. 159, 220–226.

645 Mackintosh, J.A., 2001. The antimicrobial properties of melanocytes, melanosomes and
646 melanin and the evolution of black skin. J. Theor. Biol. 211, 101–113.

647 Mai, W., Liu, P., Chen, H., Zhou, Y., 2014. Cloning and immune characterization of the c-
648 type lysozyme gene in red-spotted grouper, *Epinephelus akaara*. Fish & Shellfish
649 Immunol. 36, 305–14.

650 Malham, S.K., 1996. Immunobiology of *Eledone cirrhosa* (Lamarck). University of Wales,
651 Bangor, North Wales, UK.

652 Malham, S.K., Runham, N.W., Secombes, C.J., 1998. Lysozyme and antiprotease activity in
653 the lesser octopus *Eledone cirrhosa* (Lam.) (Cephalopoda). Dev. Comp. Immunol. 22,
654 27–37.

655 Mangold, K., Bidder, A.M., 1989. Appareils respiratoire et circulatoire : respiration et
656 circulation, in: Traité de Zoologie, Anatomie, Systématique, Biologie. Céphalopodes,
657 Tome V. Grassé, Pierre-Paul, Paris, pp. 387–434.

658 Manubens, A., Salazar, F., Haussmann, D., Figueroa, J., Del Campo, M., Pinto, J.M.,
659 Huaquín, L., Venegas, A., Becker, M.I., 2010. Concholepas hemocyanin biosynthesis
660 takes place in the hepatopancreas, with hemocytes being involved in its metabolism. Cell
661 Tissue Res. 342, 423–435.

662 Martoja, M., Marcaillou, C., 1993. Localisation cytologique du cuivre et de quelques autres
663 métaux dans la glande digestive de la seiche, *Sepia officinalis* L. (Mollusque
664 Céphalopode). Can. J. Fish. Aquat. Sci. 50, 542–550.

665 Masuda, T., Otomo, R., Kuyama, H., Momoji, K., Tonomoto, M., Sakai, S., Nishimura, O.,
666 Sugawara, T., Hirata, T., 2012. A novel type of prophenoloxidase from the kuruma
667 prawn *Marsupenaeus japonicus* contributes to the melanization of plasma in crustaceans.
668 Fish & Shellfish Immunol. 32, 61–68.

669 McFall-Ngai, M., Nyholm, S. V, Castillo, M.G., 2010. The role of the immune system in the
670 initiation and persistence of the *Euprymna scolopes*-*Vibrio fischeri* symbiosis. Semin.
671 Immunol. 22, 48–53.

672 Messenger, J.B., 2001. Cephalopod chromatophores: neurobiology and natural history. Biol.
673 Rev. Camb. Philos. Soc. 76, 473–528.

674 Miramand, P., Bentley, D., 1992. Concentration and distribution of heavy metals in tissues of
675 two cephalopods, *Eledone cirrhosa* and *Sepia officinalis*, from the Rench coast of the
676 English Channel. Mar. Biol. 114, 407–414.

677 Miramand, P., Guary, J.C., 1980. High concentrations of some heavy metals in tissues of the
678 Mediterranean *Octopus*. Bull. Environ. Contam. Toxicol. 24, 783–788.

679 Nagai, H., 2012. Protein Toxin of Cephalopods, in: Fattorusso, E., Gerwick, W.H.,
680 Taglialatela-Scafati, O. (Eds.), Handbook of Marine Natural Products. Springer
681 Netherlands, Dordrecht, pp. 1412–1413.

682 Park, J.-W., Kim, C.-H., Kim, J.-H., Je, B.-R., Roh, K.-B., Kim, S.-J., Lee, H.-H., Ryu, J.-H.,
683 Lim, J.-H., Oh, B.-H., Lee, W.-J., Ha, N.-C., Lee, B.-L., 2007. Clustering of
684 peptidoglycan recognition protein-SA is required for sensing lysine-type peptidoglycan
685 in insects. Proc. Natl. Acad. Sci. U. S. A. 104, 6602–7.

686 Perrin, A., 2004. Etude expérimentale des capacités digestives chez la seiche, *Sepia officinalis*
687 L. (Mollusque, Céphalopode): Impact de l'alimentation, indice de condition
688 nutritionnelle et formulation d'un aliment artificiel. Université de Caen.

689 Pryor, M.G.M., 1940. On the hardening of the cuticle of insects. Proc. R. Soc. London. Ser. B
690 128, 393–407.

691 Rao, X.-J., Ling, E., Yu, X.-Q., 2010. The role of lysozyme in the prophenoloxidase
692 activation system of *Manduca sexta*: an *in vitro* approach. Dev. & Comp. Immunol. 34,
693 264–71.

694 Rocca, E., 1969. Copper distribution in *Octopus vulgaris* Lam. hepatopancreas. Comp.
695 Biochem. Physiol. 28, 67–82.

696 Rögener, W., Renwrantz, L., Unlenbruck, G., 1985. Isolation and characterization of a lectin
697 from the hemolymph of the cephalopod *Octopus vulgaris* (Lam.) inhibited by α-d-lactose
698 and N-acetyl-lactosamine. Dev. & Comp. Immunol. 9, 605–616.

699 Rowley, A.F., Powell, A., 2007. Invertebrate immune systems specific, quasi-specific, or
700 nonspecific? J. Immunol. 179, 7209–7214.

701 Ruth, P., Blum, W., Bille, J., 1996. Immunocytochemical reaction of a haemocyanin antibody
702 in the midgut gland of *Nautilus* (Cephalopoda, Tetrabranchiata). Experientia 52, 549–
703 553.

704 Safi, G., 2013. Etude de la variabilité spatio-temporelle des caractéristiques physiologiques
705 des jeunes stades de vie de la seiche *Sepia officinalis* L . en Manche. Université de Caen
706 Basse-Normandie.

707 Saurabh, S., Sahoo, P.K., 2008. Lysozyme: an important defence molecule of fish innate
708 immune system. Aquac. Res. 39, 223–239.

709 Schipp, R., 1987. The blood vessels of cephalopods. A comparative morphological and
710 functional survey. Experientia 43, 525–537.

711 Schipp, R., Boletzky, S. von, 1975. Morphology and function of the excretory organs in
712 dibranchiate Cephalopods. Fortschr. Zool. 23, 89–11.

713 Schipp, R., Boletzky, S. von, 1976. The pancreatic appendages of dibranchiate cephalopods.
714 I. The fine structure of the "Pancreas" in Sepioidea. Zoomorphologie 86, 81–98.

715 Schipp, R., Hevert, F., 1978. Distribution of copper and iron in some central organs of *Sepia*
716 *officinalis* (Cephalopoda). A comparative study by flameless atomic absorption and
717 electron microscopy. Mar. Biol. 47, 391–399.

718 Schipp, R., Hevert, F., 1981. Ultrafiltration in the branchial heart appendage of dibranchiate
719 cephalopods: a comparative ultrastructural and physiological study. J. Exp. Biol. 92, 23–
720 35.

721 Schipp, R., Höhn, P., Ginkel, G., 1973. Elektronenmikroskopische und histochemische
722 Untersuchungen zur funktion der branchialdrüse (parabranchialdrüse) der Cephalopoda.
723 Zeitschrift für Zellforsch. und Mikroskopische Anat. 139, 253–269.

724 Schipp, R., Höhn, P., Schäfer, A., 1971. Elektronenmikroskopische und histochemische
725 untersuchungen zur funktion des kiemenherzanhanges (pericardialdrüse) von *Sepia*
726 *officinalis*. Zeitschrift für Zellforsch. und mikroskopische Anat. 117, 252–274.

727 Schipp, R., Mollenhauer, S., Boletzky, S. von, 1979. Electron microscopical and
728 histochemical studies of differentiation and function of the cephalopod gill (*Sepia*
729 *officinalis* L.). Zoomorphologie 93, 193–207.

730 Siddiqui, N.I., Akosung, R.F., Gielens, C., 2006. Location of intrinsic and inducible
731 phenoloxidase activity in molluscan hemocyanin. Biochem. Biophys. Res. Commun.
732 348, 1138–1144.

733 Söderhäll, K., Cerenius, L., 1998. Role of the prophenoloxidase-activating system in
734 invertebrate immunity. Curr. Opin. Immunol. 10, 23–28.

735 Sof'ina, E.Y., Akhnedzhanov, R.A., Pivnenko, T.N., Epshtein, L.M., 1988. Trypsin inhibitor
736 from liver of the squid *Berryteuthis magister*. Chem. Nat. Compd. 24, 760–761.

737 Stuart, A.E., 1968. The reticulo-endothelial apparatus of the lesser octopus, *Eledone cirrhosa*.
738 J. Pathol. Bacteriol. 96, 401–412.

739 Thøgersen, I.B., Salvesen, G., Brucato, F.H., Pizzo, S. V, Enghild, J.J., 1992. Purification and
740 characterization of an α-macroglobulin proteinase inhibitor from the mollusc *Octopus*
741 *vulgaris*. Biochem. J. 285, 521–527.

742 Thomas-Guyon, H., Gagnaire, B., Bado-Nilles, A., Bouilly, K., Lapègue, S., Renault, T.,
743 2009. Detection of phenoloxidase activity in early stages of the Pacific oyster
744 *Crassostrea gigas* (Thunberg). Dev. Comp. Immunol. 33, 653–659.

745 Thompson, I., Choubert, G., Houlihan, D.F., Secombes, C.J., 1995. The effect of dietary
746 vitamin A and astaxanthin on the immunocompetence of rainbow trout. Aquaculture
747 133, 91–102.

748 Tschesche, H., Dietl, T., 1972. Identifizierung der proteaseinhibitoren synthetisierenden
749 organe der weinbergschnecke (*Helix pomatia*). Hoppe. Seylers. Z. Physiol. Chem. 353,
750 1189–1193.

751 Tschesche, H., von Rücker, A., 1973. Über die organverteilung der proteinase-inhibitoren
752 breiter spezifität aus Tintenfischen (*Loligo vulgaris*). Hoppe. Seylers. Z. Physiol. Chem.
753 354, 1510–1512.

754 Undheim, E. a B., Georgieva, D.N., Thoen, H.H., Norman, J. a, Mork, J., Betzel, C., Fry,
755 B.G., 2010. Venom on ice: first insights into Antarctic octopus venoms. Toxicon 56,
756 897–913.

757 Vanhoorelbeke, K., Goossens, A., Gielsens, C., Préaux, G., 1994. An α_2-macroglobulin-like
758 proteinase inhibitor in the haemolymph of the Decabrachia cephalopod *Sepia officinalis*.
759 Arch. Int. Physiol. Biochim. Biophys. 102, B25.

760 Wang, L., Qiu, L., Zhou, Z., Song, L., 2013. Research progress on the mollusc immunity in
761 China. Dev. & Comp. Immunol. 39, 2–10.

762 Wang, X.-W., Wang, J.-X., 2013. Diversity and multiple functions of lectins in shrimp
763 immunity. Dev. & Comp. Immunol. 39, 27–38.

764 Wang, Z., Zhang, S., 2010. The role of lysozyme and complement in the antibacterial activity
765 of zebrafish (*Danio rerio*) egg cytosol. Fish & Shellfish Immunol. 29, 773–7.

766 Wells, M.J., Wells, J., 1989. Water uptake in a cephalopod and the function of the so-called
767 "Pancreas". J. Exp. Biol. 145, 215–226.

768 Wilson, R., Ratcliffe, N.A., 2000. Effect of lysozyme on the lectin-mediated phagocytosis of
769 *Bacillus cereus* by haemocytes of the cockroach, *Blaberus discoidalis*. J. Insect Physiol.
770 46, 663–670.

771 Won, J.H., Hong, S.H., Shim, W.J., Yim, U.H., Kim, G.B., 2009. Persistent organochlorine
772 pollutants in Korean offshore waters: squid (*Todarodes pacificus*) as a biomonitor. Mar.
773 Pollut. Bull. 58, 1238–44.

774 Xue, Q., Itoh, N., Schey, K.L., Cooper, R.K., La Peyre, J.F., 2009. Evidence indicating the
775 existence of a novel family of serine protease inhibitors that may be involved in marine
776 invertebrate immunity. Fish & Shellfish Immunol. 27, 250–259.

777 Yamada, H., Takayanagi, K., Tateishi, M., Tagata, H., Ikeda, K., 1997. Organotin compounds
778 and polychlorinated biphenyls of livers in squid collected from coastal waters and open
779 oceans. Environ. Pollut. 96, 217–26.

780 Zanna, P.T., Maida, I., Arciuli, M., Jimenez-Cervantes, C., Garcia-Borron, J.C., Cicero, R.,
781 Guida, G., 2009. Molecular cloning and biochemical characterization of the skin
782 tyrosinase from *Rana esculenta* L. Comp. Biochem. Physiol. Part B Biochem. & Mol.
783 Biol. 152, 234–242.

784 Zhao, J., Qiu, L., Ning, X., Chen, A., Wu, H., Li, C., 2010. Cloning and characterization of an
785 invertebrate type lysozyme from *Venerupis philippinarum*. Comp. Biochem. Physiol. B.
786 Biochem. Mol. Biol. 156, 56–60.

787 Zhou, Z., Ni, D., Wang, M., Wang, Lingling, Wang, Leilei, Shi, X., Yue, F., Liu, R., Song,
788 L., 2012. The phenoloxidase activity and antibacterial function of a tyrosinase from
789 scallop *Chlamys farreri*. Fish Shellfish Immunol. 33, 375–81.

790

791 **Legends**

792 **Figure 1:** PO-like and APO-like activities (U mg prot^{-1}) in 13 body compartments of
793 cuttlefish *Sepia officinalis* L. BH: branchial hearts, BHA: branchial heart appendages, SH:
794 systemic heart, DG: digestive gland, DGA: digestive gland appendages, PSG: posterior
795 salivary glands, Stc: stomach, WB: white bodies. The bars represent the means (± SE) of 10
796 animals. Subscript letters indicate one-way ANOVA results within each activity group (PO-
797 or APO-like): bars with same subscript letter are not significantly different ($p<0.05$). *, **
798 and ***, indicate significant PO- and APO-like activity differences in each organs for $p<0.05$,
799 $p<0.01$ and $p<0.001$, respectively.

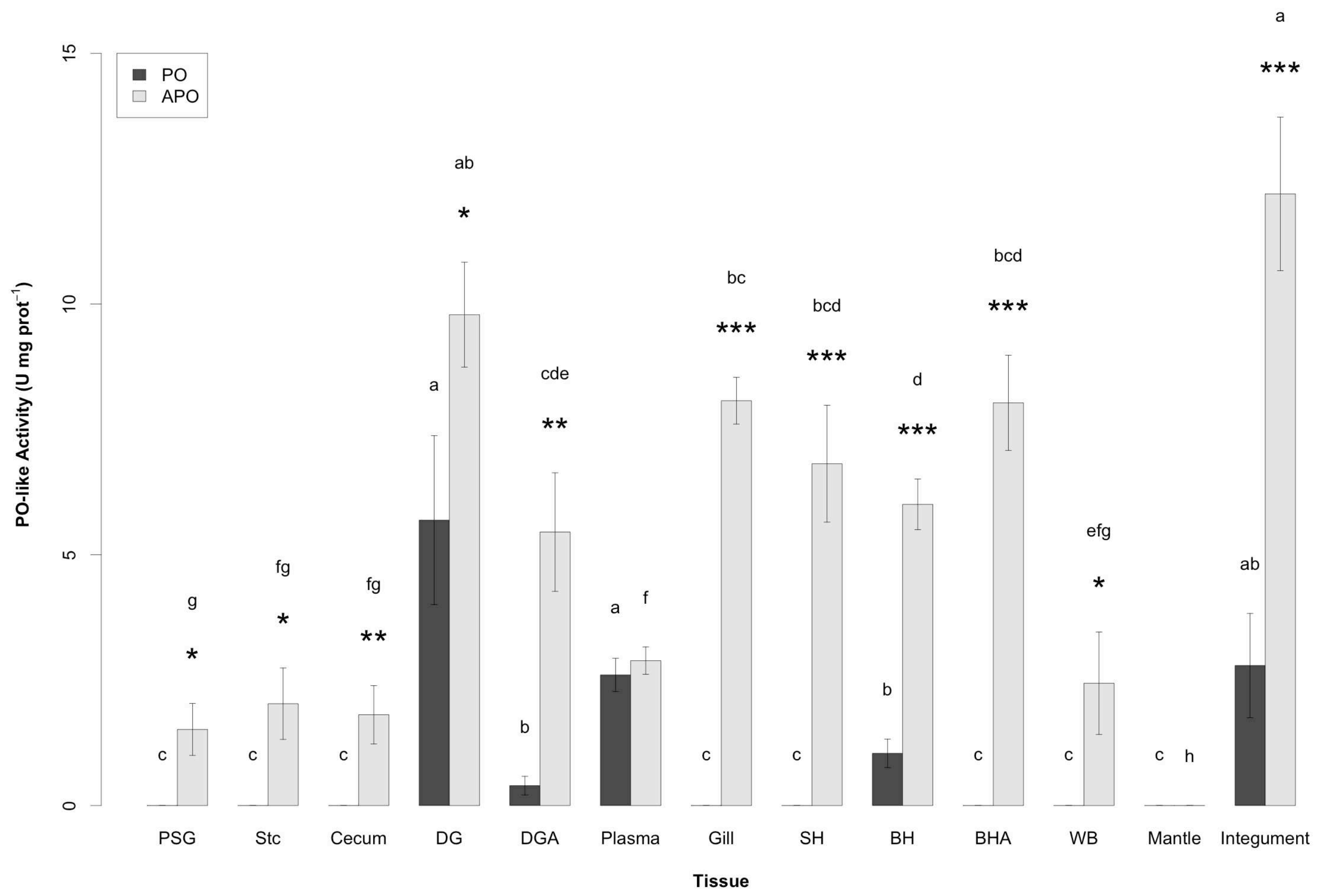
800 **Figure 2:** Lysozyme-like activity (µg HEW Lysozyme eq. mg prot^{-1}) in 13 body
801 compartments of cuttlefish *Sepia officinalis* L. BH: branchial hearts, BHA: branchial heart
802 appendages, SH: systemic heart, DG: digestive gland, DGA: digestive gland appendages,
803 PSG: posterior salivary glands, Stc: stomach, WB: white bodies. The bars represent the means
804 (± SE) of 10 animals. Bars with same subscript letter are not significantly different ($p<0.05$).

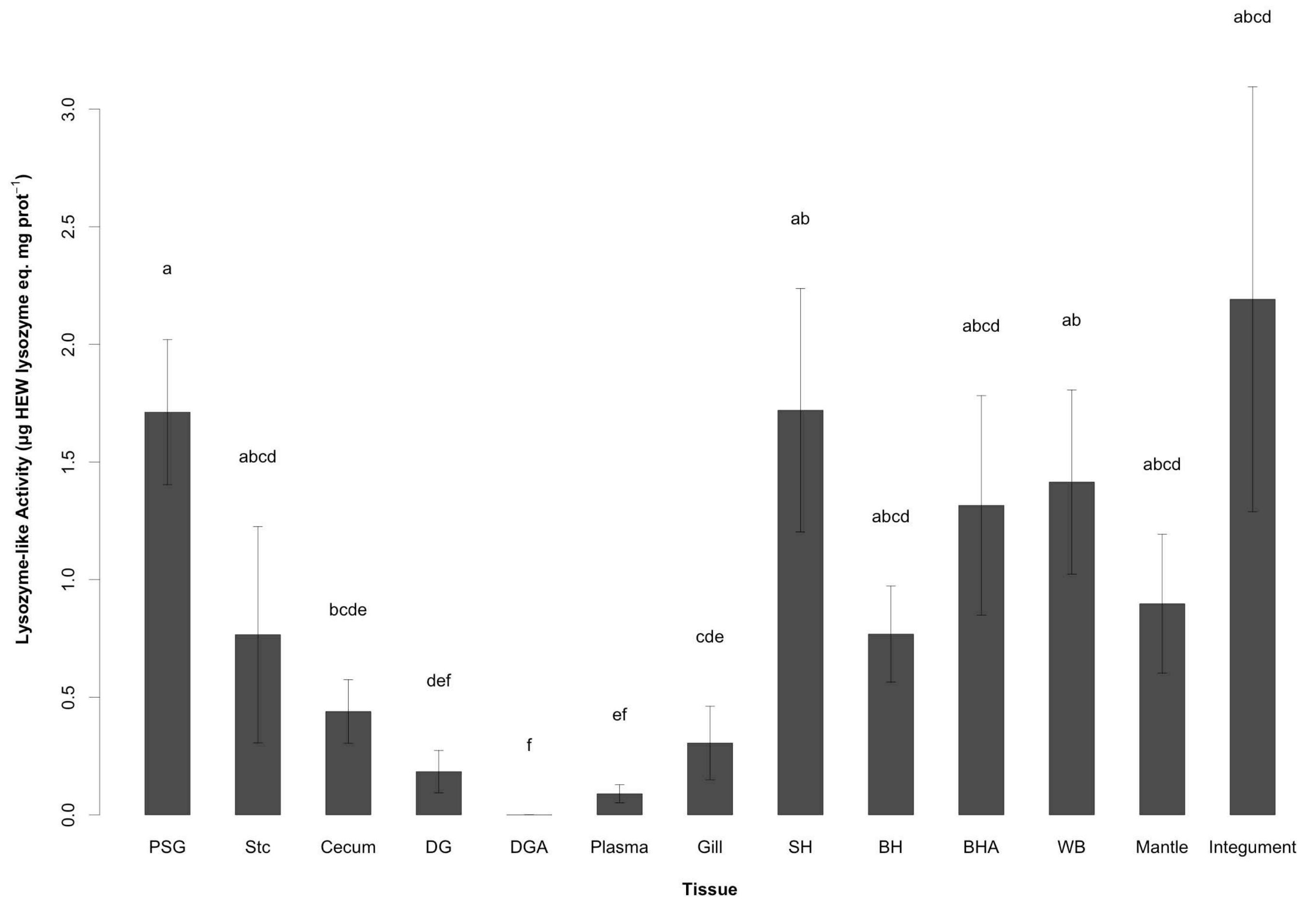
805 **Figure 3:** PI activity (TI % µg prot^{-1}) in 13 body compartments of cuttlefish *Sepia officinalis*
806 L. BH: branchial hearts, BHA: branchial heart appendages, SH: systemic heart, DG: digestive
807 gland, DGA: digestive gland appendages, PSG: posterior salivary glands, Stc: stomach, WB:
808 white bodies. The bars represent the means (± SE) of 10 animals. Bars with same subscript
809 letter are not significantly different ($p<0.05$).

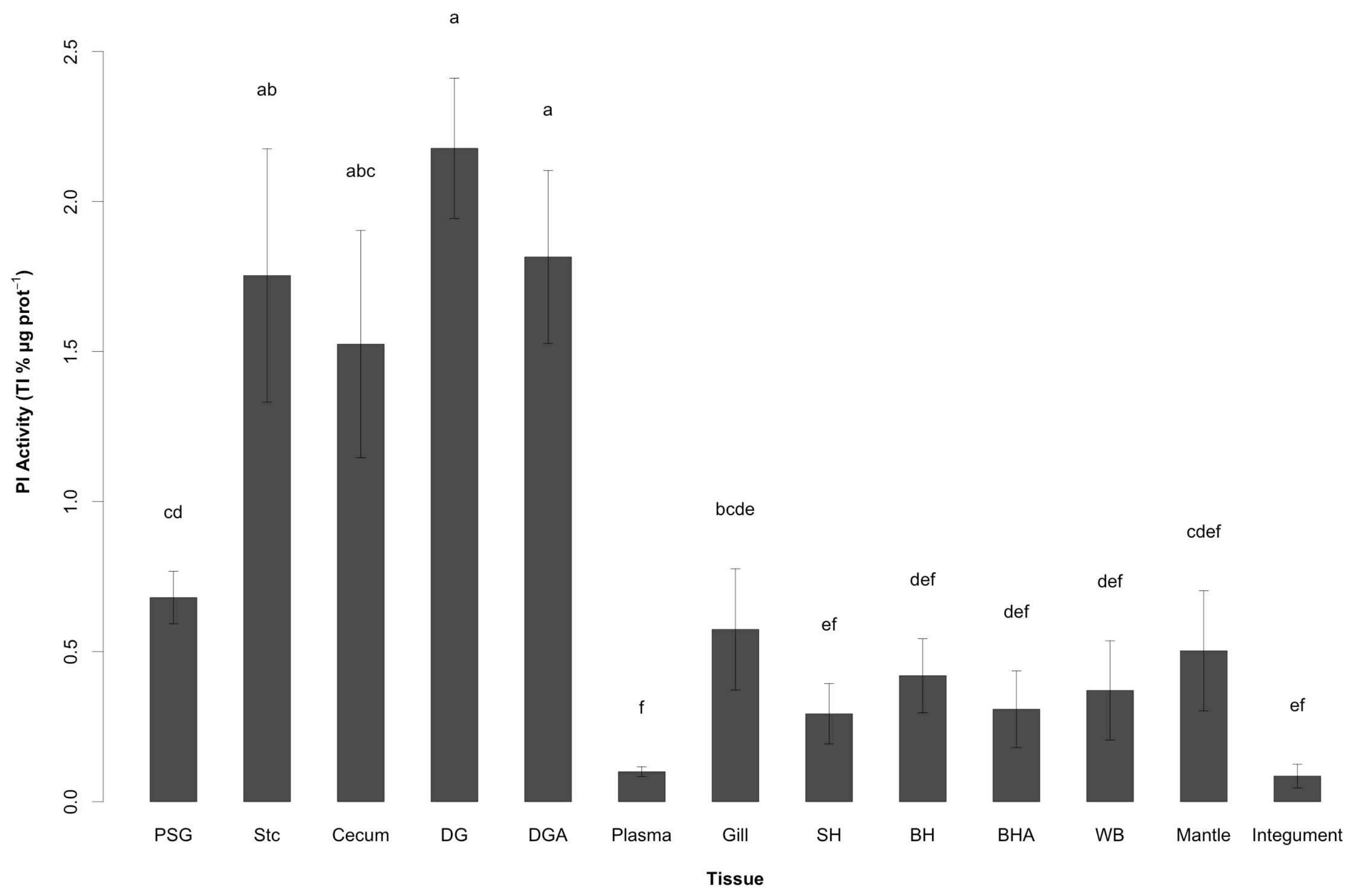
810 **Legends to supplementary files**

811 **Figure 1S:** Internal anatomy of cuttlefish *Sepia officinalis* L., with studied tissues. BH:
812 branchial hearts, BHA: branchial heart appendages, SH: systemic heart, DG: digestive gland,
813 DGA: digestive gland appendages, PSG: posterior salivary glands, Stc: stomach, WB: white
814 bodies (modified after Boyle and Rodhouse, 2005).

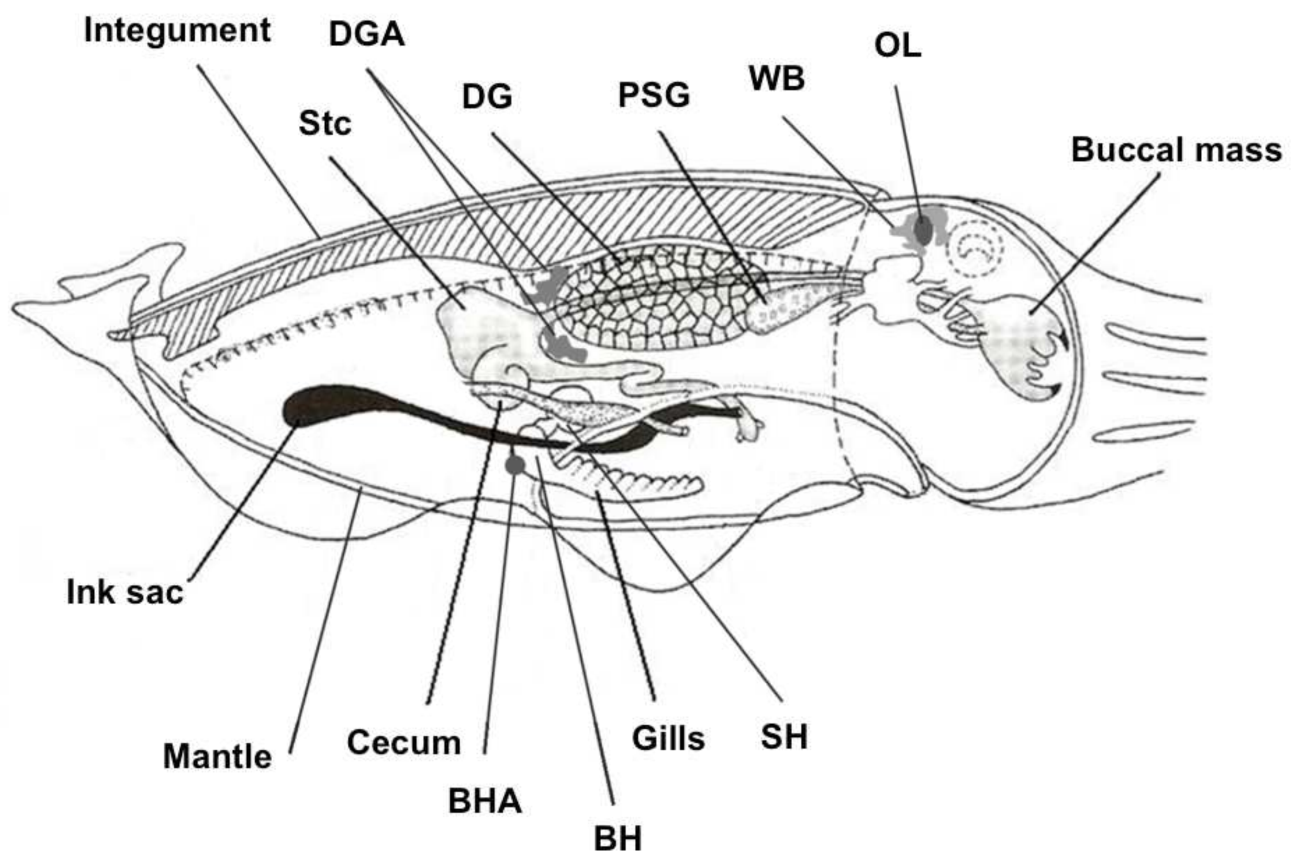
815


PO
APO
PO-like Activity (U mg prot^{-1})
0
5
10
15
Tissue
PSG
Stc
Cecum
DG
DGA
Plasma
Gill
SH
BH
BHA
WB
Mantle
Integument
g
fg
fg
ab
a
cde
b
a
f
bc
bcd
d
b
bcd
efg
c
h
ab
a
*
**
***


Lysozyme-like Activity (µg HEW lysozyme eq. mg prot^{-1})
0.0
0.5
1.0
1.5
2.0
2.5
3.0
a
abcd
bcde
def
f
ef
cde
ab
abcd
abcd
ab
abcd
abcd
PSG
Stc
Cecum
DG
DGA
Plasma
Gill
SH
BH
BHA
WB
Mantle
Integument
Tissue



PI Activity (TI % µg prot⁻¹)
0.0
0.5
1.0
1.5
2.0
2.5
cd
ab
abc
a
a
f
bcde
ef
def
def
def
cdef
ef
PSG
Stc
Cecum
DG
DGA
Plasma
Gill
SH
BH
BHA
WB
Mantle
Integument
Tissue


Integument
DGA
DG
PSG
WB
OL
Stc
Buccal mass
Ink sac
Mantle
Cecum
BHA
BH
Gills
SH