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1 Reversibility of trace metals effects on sea urchin embryonic development

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10

11 Abstract

12 The sea urchin embryo-toxicity test is widely used to assess the toxicity of contaminants and environmental matrices. In standard guideline and literature studies, the classical toxicity criteria are 13 based on distinguishing between normal and abnormal embryos at pluteus stage. The aim of this research 14 was to further expand the potentiality of the recently developed Integrative Toxicity Index (ITI) 15 investigating the reversibility of the effects induced by various trace metals (cadmium, copper, lead and 16 zinc) on sea urchin development. For this purpose, embryos were observed after different periods of 17 exposure and recovery to metals. Results were analysed comparing ITI with standard criteria, thus 18 moving from the simple observation of general effects to the classification of their severity. The onset 19 and reversibility of effects by trace metals were more efficiently discriminated by the use of the ITI, 20 21 which recognized and weighted the delay and degree of various abnormalities. Overall, this study confirmed the enhanced capability of ITI in assessing interferences of pollutants on sea urchin 22 23 development, supporting a more accurate use of this embryo-toxicity assay in various practical applications. 24

25

26 Keywords: Paracentrotus lividus, Toxicity index, Trace metals, Reversibility, Developmental

27 anomalies

28 1. Introduction

Urban and industrial activities in coastal areas introduce significant amounts of pollutants and metals certainly represent one of the classes of major concern for their toxicological potential toward marine organisms. Many biomonitoring studies and normative guidelines integrate the analyses on chemical characterization of abiotic matrices with the assessment of their effects at different levels of biological organization, from molecular changes up to community disturbance. The use of ecotoxicological bioassays is a widely recognized approach to evaluate toxicological endpoints at organism level, using a
wide selection of biological endpoints and species of different trophic levels in standardized conditions.
Bioassays with embryos of marine invertebrates are routinely used to assess the ecotoxicological quality
of environmental matrices, and the sea urchin is one of the most sensitive and widespread choice, which
allowed to demonstrate the teratogenic effects of trace metals from the elutriate of marine sediments or
seawater (His et al. 1999; Beiras et al. 2003; Kobayashi and Okamura 2004, 2005; Khosrovyan et al.
2015; Rodríguez-Romero 2016; Morroni et al. 2016).

Many authors have characterized dose–response relationships exposing sea urchin embryos to increasing concentrations of individual metals or mixtures (Warnau et al. 1996; Fernàndez and Beiras 2001; Radenac et al. 2001; Arizzi Novelli et al. 2003; Xu et al. 2011): in these studies embryos were typically classified at pluteus stage as normal/abnormal, calculating their relative percentages to estimate metal toxicity. More detailed toxic effects of xenobiotics on gametes and specific developmental stages were investigated since several decades (Pagano et al. 1982; Graillet et al. 1993).

Although these studies extensively describes alterations of embryo morphology, such effects have rarely 47 been taken into consideration to develop a standardized scale of toxicity assigning a different weight to 48 various embryonic malformations depending on their severity and reversibility during the embryonic 49 50 development. While Carballeira et al. (2012) proposed to calculate the percentage of abnormal larvae classifying embryos based on their observed skeletal malformations, a more recent study proposed a new 51 toxicity scale associating different values to each morphotype in relation to specific malformations and 52 developmental stage of sea urchin embryos (Morroni et al. 2016). This approach allows for a better 53 54 categorization of the teratogenic potential of environmental matrices and chemicals through a more 55 sensitive and realistic integrative toxicity index (ITI), moving from the simple observation of general effects to the classification of their severity. 56

With the aim of further testing the potentiality of the new integrative toxicity index, improving the 57 ecological relevance of the embryo toxicity bioassay, this study focussed on the possible reversibility of 58 59 teratogenic effects described for common trace metals such as cadmium (Cd), copper (Cu), lead (Pb) and zinc (Zn). In this respect, experiments performed with embryos continuously exposed to various metals 60 from fertilization up to the pluteus stage (72 hours), were compared with treatments in which each metal 61 was removed after 24 hours, and embryos monitored in clean seawater during the following 48 hours of 62 recovery phase. Results were evaluated both in terms of ITI and in terms of adopting the standard 63 endpoints of normal/abnormal embryos. The overall comparison of the evaluation procedures and of 64 65 results obtained from different experimental treatments was expected to provide new insights on the

capability of each metal to induce anomalies leading to a block or delay in embryogenesis of the embryos
to recover normal development after metal exposure, thus adding further ecological value to sea urchin
bioassay.

69

70 2. Materials and methods

71 2.1 Sea urchin fertilization and embryo toxicity experiments

Adult sea urchins (*P. lividus*) were collected during the breeding season by free divers along the southern 72 coast of Livorno, Italy (43° 25.602' N – 10° 23.780' E). After collection, the sea urchins were transported 73 in an insulated container to the laboratory and acclimatized for up to one week in flowing seawater at a 74 temperature of 15° C \pm 1, salinity 38 and natural photoperiod. Embryotoxicity tests were performed in 75 accordance with standard procedure (ASTM 2004) and literature data (Volpi Ghirardini et al. 2005). 76 Three males and three females were induced to spawn by injecting 1 ml of 0.5 M KCl into the sea urchin 77 body cavity through the peristomial membrane surrounding the mouth. Eggs were collected by placing 78 spawning females on 100 ml beakers with 0.45 µm FSW collected at the same site as the sea urchins. 79 Once mobility was checked, 5 µl of sperms were diluted in 50 ml of FSW and added to 350 ml of egg 80 suspension (1000 eggs/ml), sperm/egg ratio 50:1. After fertilization, embryos were exposed for 72 h to 81 increasing concentrations of Cd, Cu, Pb and Zn (Table 1). Control embryos were exposed to FSW only. 82 To evaluate the reversibility of induced effects, additional experiments were performed in which metals 83 were removed after 24 h of development/exposure (gastrula stage). The same treatment was applied to 84 control embryos in order to verify the absence of any embryo alteration due to the washing procedure. 85 Specifically, embryos were filtered using a 55 µm nylon mesh in order to remove them from the metal 86 solution, and then cultured in clean FSW during the following 48 h of recovery phase (from 24 to 72 h 87 after fertilization). Washed embryos were compared with embryos continuously exposed from 88 fertilization to the pluteus stage (72 h post-fertilization) (non-washed embryos). Metal-induced 89 90 malformations were analysed at 24 h, 48 h and 72 h development/exposure (Table 1S). Embryos exposed to Cd, Cu, Pb, Zn were maintained in 10 ml sterile capped polystyrene six-well micro-plates (1 ml per 91 well, corresponding to a final density about 100 embryos/ml) at a temperature of 20 °C in a dark room. 92 Three replicates for each sample were carried out. At the end of the experiment samples were preserved 93 by adding a few drops of 40% buffered formalin and morphological evaluation was performed. 94

Tests were accepted if the percentage of control embryos at 48 h of development (negative control) was $\geq 80\%$. Reference toxicant results (continuously Cu-exposed embryos) were accepted if they fell within

- 97 the laboratory acceptability ranges (between 34.598 and 68.344 μ g/l) and literature data (Beiras and 98 Fernàndez 2001) at 48 h of development/exposure.
- 99

100 *2.2 Toxicity criteria*

101 The degree of metal toxicity was calculated using the integrative toxicity index (ITI) (Morroni et al.

- 2016) and the standard criteria of evaluation based on the calculation of the percentage of normal versusabnormal embryos.
- 104 Groups of 100 embryos were analysed at 24, 48 and 72 hours (h) by optical microscopy (Leica 105 DMI3000B) and photographed using a digital camera (Leica DCF450C).
- Embryos were classified as normal only when they satisfied all the following morphological criteria: (1) correct schedule in reaching the developmental endpoint, (2) left/right and dorso/ventral embryonic axis symmetry, (3) differentiation of oral/aboral ectoderm and endoderm. ITI was calculated by assigning a
- different weight to various embryonic malformations depending on both their severity and the stage at
 which malformations (delayed and/or abnormal embryos morphologies) appeared, quantified based on a
- ranking of severity from 0 (none) to 10 (high). Lower toxicity values were given to delayed embryos
 (embryos with delay in development and absence of malformations) and higher scores were attributed to
- abnormal embryos (embryos with delay in development and malformations) with no chance to recover
- development. The toxicity categories are shown in Table 2S and ITI is calculated as follows:
- 115 ITI = $\sum_{i=10}^{n} (S_i * F_i) / 100$
- 116 Where S_i is the score associated to each abnormality and F_i is the frequency observed for that abnormality 117 (i=10).
- 118

119 *2.3 Chemical test and analysis of metals*

The concentrations of Cd, Cu and Zn were analysed by inductively coupled plasma optical emission spectrometry (ICP-OES) and the concentration of Pb by Atomic Absorption Spectrometry (AAS). The results showed that measured concentrations generally varied less than 15% from the nominal concentrations (see Table 3S). Thus, all calculations were based on nominal concentrations.

- 124
- 125 *2.4 Data analysis*

126 Variations in embryo development related to metal exposure, incubation time and washing treatment 127 were examined through a permutational multivariate analysis of variance (PERMANOVA, Anderson 128 2001). The analyses were computed on a resemblance matrix, obtained by applying the Euclidean 129 distance index, and all observed morphotypes were considered as variables. Metal concentration, incubation time and washing were considered as fixed factors. When significant differences in embryo 130 development were detected, additional pair-wise tests were performed. Primer v6 statistical package in 131 conjunction with the Windows PERMANOVA + module (Anderson et al. 2008) were used to perform 132 the statistical tests. The percentages of abnormal larvae and size inhibition were also considered to 133 evaluate the toxic effects estimated as EC50 values. The EC values with 95% confidence limits were 134 calculated by the Trimmed Spearman-Karber statistical method. Responses in each experimental 135 condition were corrected for effects in control tests by applying Abbott's formula (Hamilton et al. 1978). 136

137

Metal	μg/L	М
Cd	1000, 1500, 2000, 2500	8.89x10 ⁻⁶ , 1.33 x 10 ⁻⁵ , 1.78 x 10 ⁻⁵ , 2.22 x 10 ⁻⁵
Cu	20, 50, 60, 70	3.15 x 10 ⁻⁷ , 7.87 x 10 ⁻⁷ , 9.44 x 10 ⁻⁷ , 1.10 x 10 ⁻⁶
Рb	80, 100, 120, 250	3.86 x 10 ⁻⁷ , 4.8 x 10 ⁻⁷ , 5.79 x 10 ⁻⁷ , 1.21 x 10 ⁻⁶
Zn	60, 70, 100, 120	9.47 x 10 ⁻⁷ , 1.10 x 10 ⁻⁶ , 1.58 x 10 ⁻⁶ , 1.89 x 10 ⁻⁶

138Table 1 – .Metal concentrations used in the experiments. Values are expressed in $\mu g/L$ (left part of the panel) and using molar notations139(right part of the panel).

140

141 **3. Results and discussion**

The effects observed in embryos at various experimental conditions are reported in Fig. 1, the median effective concentration (EC50) and the values of ITI are given in Table 2 and Table 3, respectively. In general, embryos perturbed for 24 h and then cultured in FSW for the following 48 h recovered development but never completely resumed their normal patterns. Negative control embryos washed with FSW did not show any harmful effects related to the washing treatment (t = 0.47, p = 0.65).

A good concentration-dependent relationship between the four trace metals and the toxicity index was 147 generally observed both during continuous exposures to Cd, Cu, Pb and Zn, and following the recovery 148 period. After 48 h, washed embryos displayed toxicity index values higher than after 24 and 72 h 149 development/exposure, with the exception of Zn-exposed embryos where the highest toxicity levels were 150 observed at 72 h (Fig. 1, Table 2 and Table 3). Considering the multivariate PERMANOVA performed 151 on all morphotypes used to estimate the index, the results showed a significant effect of various factors 152 (metal, concentration, time of incubation, washing) and their interactions. The pair-wise comparison 153 performed for the factor washing at each time level did not show significant differences at 48 h between 154 washed and non-washed embryos (t=0.538, p=0.621), while after 72 h washed embryos showed values 155 of normally developed embryos significantly higher than those measured in non-washed embryos (t= 156 157 23.354, p=0.001). As expected, an increase in recovery time typically raised the capability to restore 158 normal development (see Table 4). Specific effects depend on mechanisms by which trace metals interact with cellular components and molecular targets. In this respect, for example, an interference with calcium 159 160 homeostasis and consequently Ca-dependent signalling cascades could be responsible for such metalembryonic malformations as already demonstrated in P. lividus Mn-exposed embryos (Pinsino et al. 161 2011, 2014) and in embryos of Strongylocentrotus purpuratus exposed to Cu, Pb and Zn (Tellis et al. 162 2014a, 2014b). Cadmium (Cd) is well-known to accumulate within cells/tissues during P. lividus 163 164 development, causing teratogenesis and stimulating apoptotic processes (Agnello et al. 2006, 2007; Filosto et al. 2008). A certain delay between exposure time and the onset of visible alterations during 165 development may at least partly depend on the simultaneous effects of growth and surface adsorption of 166 the embryos. In addition, the sea urchin fertilization envelope establishes a physical and biochemical 167 barrier that protects the zygote from supernumerary sperm, as well as environmental and microbial agents 168 until hatching. In this respect, Cd, Cu, Pb and Zn apparently provoked limited effects after 24 h of 169 exposure although a different uptake mechanism causing delayed damages can not be excluded. A 170 number of published studies demonstrated that exposure of sea urchin embryos to several chemical and 171 physical stressors (including metals) induce redox anomalies, oxidative stress, DNA damage, mitotic 172 aberrations to early life stages (Pagano et al. 1996; 2016). However, embryos are prepared to counteract 173 174 environmental fluctuations by having high levels of cellular defences, buffer stress and alternative pathways that can be independent of developmental programs (Hamdoun and Epel 2007). The recovery 175 capability has important implications for the adult populations, being larval dispersal crucial for the 176 maintenance and durability of a sea urchin population. Several studies demonstrated that metal exposure 177 in *P. lividus* embryos induced the synthesis of HSPs and of metallothioneins (MT) genes (Pinsino et al. 178 179 2011), two detoxification mechanisms which can contribute to the decrease the onset of anomalies, as observed in the present study. 180

181

182 3.1 Cd-exposed embryos

Regarding the onset and reversibility of effects by specific metals, after 24 h more than 85% of embryos continuously exposed to different concentrations of Cd (from 1000 to 2500 μ g/L) displayed a normal development (EC50 value of 4183.40), with ITI values almost comparable to controls (Fig.1, Table 2 and Table 3). Conversely, at 48 h, Cd exposure was effective in producing a concentration-dependent increase of both teratogenesis (EC50 value of 1724.40) and ITI values (from 1.24 to 3.05). These effects appeared mostly related to the higher percentage of delayed (prism/early pluteus) and abnormal embryos with crossed skeletal rods (42 and 50% at 2000 and 2500 μ g/l respectively), in agreement with abnormal

embryos previously observed by Arizzi Novelli et al. (2003). Nevertheless, at 72 h of development, these authors found an EC50 value ten times lower than those reported in the present study (230 µg/l versus 2115.90 µg/l). Conversely, our results are more closely related to those obtained by Warnau et al. (1996) (3372 µg/l <EC50<11241 µg/l), and lower than those reported by Fernandez and Beiras (2001) (9240 μ g/l). Many factors, such as the physiological state of the organisms, the moment at which embryos first encounter toxicant, the water physicochemical characteristics, metal compounds used for the exposure, may influence the sensitivity of the sea urchin embryos in a different manner: these differences can also be due to methodological variations for testing, as well as the sea urchin pool of gametes utilized for the experiments. Interestingly, Pagano et al. (1982) observed that embryos exposed to Cd from hatching to pluteus stage were affected to the same extent as if treatment had stared at fertilization for the same Cd levels, meaning that the toxic effects start from hatching. Roccheri et al (2004) demonstrated that Cd removal from culture medium, after incubation for more than 15 hours (with 1 mM CdCl₂) did not allow rescuing of normal embryo development, suggesting that prolonged treatments induced irreversible damage. Authors observed a plateau stage in the synthesis of stress proteins (HSPs) after 24 hours of Cd-exposure, suggesting the existence of a threshold for this cell defence mechanism.

211	Table 2 – Toxicity results in non-washed and washed embryos, considering as endpoint the percentage of normal versus abnormal embryos.
212	Effect Concentration 50% (EC50) are given in bold and expressed in µg/l. The lower values represent the respective 95% confidence limits,
213	and the straight-line slopes (in italics).
214	

Treatment	NC	ON-WASHED EMBR	RYOS	WASHED EMBRYOS			
Incubation time	24h	48h	72h	24h	48h	72h	
Cd	4183.40	1724.40	2115.90	4183.40	1862.10	4484.90	
	(n.c.)	(1624.30-1807)	(1980.50-2258)	(n.c.)	(1425-1859)	(n.c)	
	5.90	12.15	6.87	5.90	11.74	5.33	
Cu	72.82	45.78	40.65	72.82	47.46	212.13	
	(68.24 - 82.83)	(42.36-47.89)	(36.38 - 43)	(68.24 - 82.83)	(42.03-50.65)	(111.8 - 868.5)	
	7.96	15.50	6.64	7.96	9.78	1.50	
Pb	310.68	107.88	164.45	310.68	113.38	216.70	
	(228.70-613.50)	(102.75-112.04)	(150.75 - 178.61)	(228.70-613.50)	(100.7 - 144.04)	(177.50-235.35)	
	1.73	14.40	7.10	1.73	6.66	7.88	
Zn	86.87	72.65	79.49	86.87	83.13	105.30	

(59.9-107.96)	(40.55-91.17)	(39.62 - 106.59)	(59.90-108)	(46.47-99.69)	(100.97 - 108.70)
2.34	9.34	7.82	2.34	10.61	15.88

		2.5	7	2.54	/	02	2.54		10.01	15	.00	
215												
216												
217	Table 3Values	of ITI	obtained for	washed	and non-washed	embryos at	different	trace metal	concentrations	and t	time	of
218	exposure/recovery.											

		NON-WASHED EMBRYOS			WASHED EMBRYOS			
				Tim	ne			
Metal	Concentration (µg/L)	24 h	48 h	72 h	24 h	48 h	72 h	
CTR	-	0.23	0.79	0.34	0.23	0.88	0.43	
Cd	1000	0.13	1.24	0.65	0.13	1.22	0.47	
	1500	0.22	1.88	1.12	0.22	1.78	0.51	
	2000	0.13	2.79	1.49	0.13	1.88	0.62	
	2500	0.45	3.05	3.83	0.45	2.76	0.98	
Cu	20	0.35	1.36	0.75	0.35	1.36	0.75	
	50	0.95	3.5	2.96	0.95	3.62	0.89	
	60	1.36	4.38	3.36	1.36	4.53	1.05	
	70	3.33	5.38	3.24	3.33	5.51	1.71	
Pb	80	0.72	1.2	0.35	0.72	0.97	0.28	
	100	0.78	2.48	0.59	0.78	0.85	0.25	
	120	0.73	2.05	0.78	0.73	1.45	0.45	
	250	1.09	4.48	2.71	1.09	4.64	1.04	
Zn	60	0.84	1.05	1.23	0.84	1.60	0.78	
	70	1.64	1.41	2.89	1.64	1.05	0.92	
	100	1.78	2.48	4.22	1.78	2.73	2.74	
	120	1.95	2.75	6.60	1.95	3.01	5.07	





Metal concentrations + incubation time

Fig. 1 –Effects of Cd, Cu, Pb and Zn on the sea urchin embryo development during continuous (non-washed) and after washing (washed embryos). Data are referred to effects after 24, 48 and 72 h of development. On X axis metal concentrations are reported in μg/l (CTR: control). Each stage of development reached by embryos is represented by bars in a colour scale from red to white. Normal embryos are rimmed in black and are late gastrula at 24 h (light blue bars) and pluteus stage at 48-72 h (white bars). Malformed embryos are represented with black spots at each stage of development. Pl: Pluteus; ePl: early Pluteus; Pr: Prism. IG: late Gastrula; mG: mid Gastrula; eG: early Gastrula; mBl: mesenchyme Blastula; Bl: Blastula; M: Morula.



72 h

ن

24 h

Table 4 – Effects of washing treatment on embryo development of *P. lividus*. Results reported on the table were obtained with
 PERMANOVA pair-wise tests performed for the factor washing at each level of time incubation and for factor time of incubation at each
 level of washing treatment. W48: washed embryos observed at 48 h of development; NW48: non-washed embryos at 48 h of
 development; W72: washed embryos at 72 h of development; NW72: washed embryos at 72 h of development. Significant p-value are

development; W/2: washed reported in bold.

226 227

	Cd		C	Cu		Pb		Zn	
Groups	t	Р	t	Р	Т	Р	Т	Р	
		(perm)		(perm)		(perm)		(perm)	
W48 vs NW48	0.229	0.931	0.215	0.961	0.240	0.898	0.072	0.998	
W48 vs W72	9.580	0.001	1.136	0.258	6.359	0.001	5.178	0.001	
NW48 vs NW72	2.136	0.026	1.080	0.292	1.733	0.103	2.512	0.001	
W72 vs NW72	13.171	0.001	6.031	0.001	8.054	0.001	5.375	0.001	

²²⁸ 229

230 If Cd insult is not too strong, embryos restore normal development (Roccheri et al 2004), probably because only a few cells are damaged and removed through apoptosis, allowing the restoring of the 231 232 physiological morphology. In agreement, in this work we found that embryos exposed to Cd for 24 h and then cultured in FSW for the following 24 h (48 h development) exhibited increased malformations with 233 234 developmental effects comparable to those of continuously exposed embryos (EC50 value of 1862.10, ITI values range from 1.22 to 2.76). On the contrary, embryos exposed to Cd for 24 h and then cultured 235 236 in FSW for the following 48 h (72 h development) appear almost totally recovered (EC50 2671.08, ITI 237 values range from 0.47 to 0.98).

238

239 3.2 Cu-exposed embryos

Cu-exposed embryos (from 20 to 70 µg/L) displayed a moderate number of abnormalities after 24 h 240 (EC50 values of 72.82), with a dose-dependent increase of ITI values (from 0.35 to 3.33) mostly 241 associated to a high number of abnormal mesenchyme blastula (Fig.1, Table 2 and Table 3). At 48 h of 242 development/exposure, Cu induced a great number of malformed prisms with a severe impairment of the 243 skeletal architecture of the embryos (e.g. crossed and separated tip at the hood apex arms, fused arms, as 244 well as incomplete or absent skeletal rods) (EC50 45.78, ITI values range from 1.36 to 5.38). Embryos 245 exposed to Cu for 24 h and then cultured in FSW for a following rescue period of 24 h (48 h development) 246 showed a marked increase of malformations, with embryo toxicity values fully comparable to those of 247 48 h continuously exposed embryos (EC50 47.46, ITI values range from 1.36 to 5.51). 248

In agreement with data from Warnau *et al.* (1996) (48 μ g/l <EC50<64 μ g/l), Radenac et al. (2001) (50

250 μg/l <EC50< 100 μg/l), Arizzi Novelli *et al.* (2003) (62 μg/l) and Fernandèz and Beiras (2001) (66.76

 μ g/l), at 72 h of development, the majority of Cu-exposed embryos showed a prismoid shape, with

slightly increased values of developmental anomalies (EC50 40.65, ITI values range from 0.75 to 3.24). 252 The reversibility of effects was more evident in embryos exposed to Cu for 24 h and then cultured in 253 FSW for a following rescue period of 48 h, showing an elevated capability to recover normal 254 development (EC50 212.13, ITI values range from 0.75 to 1.71). To the best of our knowledge, this is 255 256 the first study underling the sea urchin embryonic recovery capability after Cu treatment.

257

258 3.3 Pb-exposed embryos

The 24 h exposure to Pb (from 80 to 250 µg/L) determined moderate teratogenic effects at the blastula 259 260 and gastrula stage including delayed embryos (EC50 310.68, ITI values range from 0.72 to 1.09). At the pluteus stage (48 h), continuously Pb-exposed embryos displayed a high number of abnormalities with a 261 262 dose-dependent trend, exhibiting crossed and separated tip at the hood apex arms, as well as a delay in the developmental schedule (EC50 107.88, ITI values range from 1.2 to 4.48). Also for lead, 24 h 263 264 depuration after 24 h exposure (48 h development) was associated with an increase of developmental effects, which did not exhibit significant differences compared to those observed in continuously exposed 265 266 embryos (EC50 113.38, ITI values range from 0.97 to 4.64).

267 At 72 h, the percentage of abnormal embryos was lower than that measured at 48 h of development/Pbexposure (EC50 164.45, ITI values range from 0.35 to 2.71). These values appears slightly higher than 268 those obtained by Radenac et al. 2001 (between 10 and 100 µg/l) and Arizzi Novelli et al. (2003) (68 269 μ g/l) but lower than the results of Fernandez and Beiras (2001) (509.5 μ g/l). Embryos exposed to Pb for 270 24 h and then cultured in FSW for the following 48 h (72 h development) showed an elevated capability 271 to recover normal development (EC50 216.70, ITI values range from 0.28 to 1.04). However, at the 272 highest Pb concentration (250 µg/L), more than 70% of washed embryos reached the pluteus stage but 273 274 exhibited a severe inhibition of skeleton formation, confirming that such kind of malformations are more difficult to rescue even when development is recovered (Pinsino et al. 2011). 275

3.4 Zn-exposed embryos 276

- Exposure to Zn (from 60 to 120 μ g/L) caused a moderate number of abnormalities after 24 h (EC50 277
- values of 86.87), with ITI values higher than those observed for Cd and Pb (from 0.84 to 1.95, Fig.1, 279 Table 2 and Table 3). At the pluteus stage (48 h), continuously exposed embryos showed a high number
- 280 of delayed embryos (prismoid shape), and a moderate number of skeletal malformed embryos (EC50
- 281 72.65, ITI values from 1.05 to 2.75). Embryos exposed to Zn for 24 h and then cultured in FSW for a
- following rescue period of 24 h (48 h development) showed an evident incapability to recover a normal 282

development with effects comparable to those of non-washed embryos (EC50 83.13, ITI values rangefrom 1.60 to 3.31).

At 72 h of development, Zn-exposed embryos showed abnormalities represented by radialized arms 285 causing, in some cases, a body shape deformation (EC50 79.49, ITI values range from 1.23 to 6.60). The 286 287 EC50 values appears comparable with the results of Radenac (2001) (between 50 and 250 μ g/l) and those estimated from Arizzi Novelli et al. (2003) (49 µg/l). These abnormalities influenced the ITI values more 288 289 than standard EC50, and similar results were obtained in embryos exposed for 24 h and then cultured in 290 FSW for 48 h (EC50 105.30, ITI values range from 0.78 to 5.07). The reversibility of effects caused by 291 Zn-exposure was the lowest among tested metals, confirming a particularly high percentage of plutei with radialized arms previously observed also in the sea urchin Anthocidaris crassispina (Kobayashi and 292 Okamura, 2004). 293

Interestingly, Tellis et al. (2014) demonstrated that during the development of the sea urchin *Strongylocentrotus purpuratus*, Zn inhibits the physiological oscillations of the intracellular calcium, essential to the correct functioning of the cell machinery, causing irreversible effects after gastrulation. In agreement, a competition with calcium uptake and internalization could be responsible for our results on embryos of *P. lividus* exposed to Zn.

299

300 4. Conclusions

Overall, results highlighted an astounding level of developmental plasticity of the sea urchin embryos 301 exposed to Cd, Cu, Pb and Zn, determined by the ability to restore the underlying developmental pattern 302 after a 48-hour recovery period. Nevertheless, even if recovery may occur, prolonging time in the 303 304 plankton due to increased development time can have a range of adverse effects on larvae, such as 305 increased predation risk, dispersal away from suitable habitat, lower settlement success and juvenile growth rate (Pechenik 1999). All trace metals caused developmental toxicity in a concentration- and 306 307 time-dependent manner, being responsible for malformations and developmental delays with Zn and Cu more toxic than Pb, and Cd. 308

The specific differences in reversibility and intensity caused by different metals are highlighted by the use of the ITI, which recognizes and weights the delay and degree of various abnormalities and allow a better discriminatory ability than standard criteria. In particular, when embryos present malformations, ITI values appear more sensitive than standard criteria, which underestimate this form of toxicity. In fact, only ITI attributes higher toxicity values at severely malformed morphotypes that, in spite of low recover ability, are not considered by the standard criteria. An example of this difference, is represented by Znexposed embryos, where the numerous morphotypes with body deformation and radialized arms (72 h) influence ITI much more than standard EC50. These results reinforce the notion that the ITI enhances the capability to discern interferences on sea urchin development in an accurate manner, appearing particularly relevant to validate the sea urchin embryo toxicity assay, and supporting its usefulness in various practical applications.

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