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Biological effects of polyphenol-rich extract and fractions from an oenological oak-derived tannin on in vitro swine sperm capacitation and fertilizing ability

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14 **BIOLOGICAL EFFECTS OF POLYPHENOL-RICH EXTRACT AND FRACTIONS FROM AN OENOLOGICAL**
15 **OAK-DERIVED TANNIN ON IN VITRO SWINE SPERM CAPACITATION AND FERTILIZING ABILITY**

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21 Dedicated to the memory of Carmela Spatafora

22

23

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28

29 **Abstract**

30 Although excessive ROS levels induce sperm damage, sperm capacitation is an oxidative event that
31 requires low amounts of ROS. As the antioxidant activity of the ethanol extract (TRE) of a commercial
32 oenological tannin (*Quercus robur* toasted oak wood, Tan'Activ R[®]) and its four fractions (FA, FB, FC,
33 FD) has been recently reported, the present study was set up to investigate the biological effects of
34 TRE and its fractions in an in vitro model of sperm capacitation and fertilization. Boar sperm
35 capacitation or gamete coinubation were performed in presence of TRE or its fractions (0, 1, 10,
36 100 µg/ml). TRE at the concentration of 10 µg/ml (TRE10) stimulated sperm capacitation, as it
37 increased (p<0.001) the percentage of spermatozoa with tyrosine-phosphorylated protein positivity
38 in the tail principal piece (B pattern) (67.0 ± 10.6 vs. 48.6 ± 9.0, mean ± SD for TRE10 vs. Ctr
39 respectively). Moreover T10 significantly (p<0.001) increased oocyte fertilization rate (91.9 ± 4.0 vs.
40 69.0 ± 14.8, TRE10 vs. Ctr respectively). An opposite effect of TRE at the concentration of 100 µg/ml
41 (TRE100) on both sperm capacitation (B pattern cell percentage 33.3 ± 29.2) and fertilizing ability
42 (fertilization rate 4.9 ± 8.3), associated with a higher sperm viability (67.9 ± 9.3 vs. 35.4 ± 10.8,
43 TRE100 vs. Ctr respectively) (p<0.001), was recorded. The potency of the TRE fractions seems to be
44 highest in FB followed by FC, faint in FD and nearly absent in FA. Our results show that TRE and its
45 fractions, in a different extent, exert a powerful biological effect in finely modulating capacitation
46 and sperm fertilizing ability.

47

48 **Keywords:** antioxidant, IVF, pig sperm, polyphenols, tannins

49

1. Introduction

Mammalian sperm capacitation is the process by which spermatozoa acquire the ability to fertilize the mature oocyte. It is a complex process that normally occurs in the oviduct and involves biochemical and morphological changes that make the spermatozoon competent to bind to the zona pellucida that surrounds the oocyte, penetrate it and finally fuse with the oolemma [1]. Various cellular changes occur during sperm capacitation including the activation of adenylyl cyclase producing cAMP, influx of Ca^{2+} ions, generation of reactive oxygen species (ROS), cholesterol efflux from the plasma membrane leading to an increase in its fluidity, increase of intracellular pH, and activation of protein kinases resulting in protein phosphorylation of numerous proteins on tyrosine residues among others [1-3]. An accumulating body of evidence indicates that a mild and controlled generation of ROS plays a physiological role during capacitation and acquisition of sperm fertilizing ability while ROS-specific scavengers inhibit the process [4-6]. However, when ROS levels exceed the fine balance between ROS production and scavenging going over the threshold inducing correct triggering of sperm capacitation, oxidative stress generated by the excess of ROS causes adverse effects on the sperm plasma membrane, DNA, and physiological processes, producing irreparable alterations leading to cell death [7-8].

Plants polyphenols currently are among the most studied phytochemicals because of their biological functions and health-promoting effects. An important but often neglected group of natural polyphenols are tannins. Tannins have been demonstrated to have various health benefit activities, especially antioxidant, anticarcinogenic, cardioprotective, antiinflammatory [9-12].

Oak barrels, which are widely used in winemaking, provide polyphenols to wines and are thought to play crucial roles during wine aging, a critical process not only in improving sensory properties of wines, such as flavor and aroma, but also in acquiring health protective properties [12,13].

73 Commercial oenological tannins, often added to wine to improve its organoleptic properties, have
74 different origins and one of the main source is oak wood [14].

75 Some of us recently reported a study on the ethanol extract (TRE) of a commercial oenological
76 tannin (*Quercus robur* toasted oak wood, Tan'Activ R[®], TR) and its four fractions (FA, FB, FC, FD),
77 obtained by fractionation on Amberlite XAD-16, including data about their antioxidant activity [15].

78 As sperm capacitation is a physiological process considered an oxidative event [4-6], the present
79 study was undertaken to get an insight into the biological effects of TRE and its four fractions in a
80 well defined in vitro model of pig sperm capacitation and fertilization [16-20].

81

82 **2. Materials and Methods**

83 Unless otherwise specified, all the reagents were purchased from Sigma-Aldrich (Milan, Italy).

84 The ethanol extract of the commercial Tan'Activ R[®] (TRE) was obtained as previously reported (QR2E
85 extract) [15]. The four fractions of TRE (FA, FB, FC, FD) were obtained by Amberlite XAD-16
86 fractionation as previously described (respectively for fractions X2A, X2B, X2C, X2D) [15].

87 The study was performed with the same batch of TRE and its fractions. The powder of ethanol
88 extract TRE and of the four fractions (FA, FB, FC, FD) was stored at -20°C until resuspension in DMSO
89 (100mg/ml).

90

91 **2.1. In vitro maturation of porcine oocytes (IVM)**

92 Porcine cumulus–oocyte complexes (COCs) were aspirated using a 18 gauge needle attached to a
93 10 mL disposable syringe from 4 to 6 mm follicles of ovaries collected at a local abattoir and
94 transported to the laboratory within 1 h. Under a stereomicroscope, intact COCs were selected and
95 transferred into a petri dish (35 mm, Nunclon,Denmark) prefilled with 2 mL of modified PBS
96 supplemented with 0.4% BSA (Sigma-Aldrich A3311). After three washes in NCSU 37 [21]

97 supplemented with 5.0 µg/mL insulin, 0.57 mM cysteine, 10 ng/mL epidermal growth factor (EGF),
98 50 mM β-mercaptoethanol and 10% porcine follicular fluid (IVM medium), groups of 50 COCs were
99 transferred to a Nunc 4-well multidish containing 500 µL of the same medium per well and cultured
100 at 39 °C in a humidified atmosphere of 5% CO₂ in air. For the first 22 h of in vitro maturation the
101 medium was supplemented with 1.0 mM db-cAMP, 10 IU/mL, eCG (Folligon, Intervet, Boxmeer, The
102 Netherlands) and 10 IU/mL hCG (Corulon, Intervet). For the last 22 h COCs were transferred to fresh
103 maturation medium [22]. At the end of the maturation period the oocytes were denuded by gentle
104 repeated pipetting.

105

106 **2.2. Semen collection and preparation**

107 Sperm-rich fraction of ejaculates were collected by gloved-hand technique from three mature boars
108 (Large White × Landrace × Duroc) of proven fertility aged between 2 and 3 years and extended in
109 equal volume of Androhep TM (Minitub, Tiefenbach, Germany). Only ejaculates with
110 sperm viability higher than 80% were used in the experiments. To balancing the sperm contribution
111 of each male and eliminate variability between the evaluated semen samples, the sperm-rich
112 fractions were pooled in this study.

113 Fresh semen was centrifuged at 900 x g for 2 min. After removal of supernatant, the pellet was
114 resuspended with PBS supplemented with 0.4% BSA and centrifuged again at the same condition.

115 The final pellet was resuspended with Brackett and Oliphant's medium [23] supplemented with 12
116 % heat inactivated fetal calf serum (Gibco, Invitrogen, Italy)(FCS) and 0.7 mg/ml caffeine (Sigma-
117 Aldrich C0750) (IVF medium).

118

119 **2.3. Effect of TRE on in vitro induced sperm capacitation**

120 Sperm cells were incubated for 1h at 39 °C in a humidified atmosphere of 5% CO₂ in air in Nunc 4-
121 well multidish at a final concentration of 30x10⁶ sperm/ml in IVF medium in presence of different
122 concentrations of TRE (0, 1, 10, 100 µg/ml; TRE1, TRE10, TRE100 respectively). At the end of
123 incubation period, spermatozoa were subjected to the below described evaluations.

124 **2.3.1. Evaluation of plasma membrane integrity and acrosome status**

125 For the evaluation of sperm viability, twenty five microliters of semen were incubated with 2 µl of a
126 300 µM propidium iodide (PI) stock solution and 2 µl of a 10 µM SYBR green-14 stock solution, both
127 obtained from the live/dead sperm viability kit (Molecular Probes, Inc., Eugene, OR, USA) for 5 min
128 at 37°C in the darkness. At least 200 spermatozoa per sample were scored with a Nikon Eclipse E
129 600 epifluorescence microscope (Nikon Europe BV, Badhoevedop, The Netherlands) by the same
130 observer, blinded to the experimental group of each sample. Spermatozoa stained with SYBR green-
131 14 and not stained with PI were considered as viable. Spermatozoa SYBR and PI positive and those
132 SYBR negative / PI positive were considered as cells with non-intact membrane or dead.

133 Acrosome integrity was evaluated by using a FITC-conjugated lectin from *Pisum sativum* (FITC-PSA)
134 which label acrosomal matrix glycoproteins. Spermatozoa were washed twice in PBS by
135 centrifugation, resuspended in ethanol 95% and fixed/permeabilized at 4°C for at least 30 min.
136 Aliquots of sperm suspensions were dried on heated slides and incubated with FITC-PSA solution (5
137 µg PSA-FITC/1 mL H₂O) for 20 min in darkness. After staining, slides were washed in PBS and
138 mounted with Vectashield mounting medium containing PI counterstain for DNA (Vector
139 Laboratories, Burlingame, CA, USA). The slides were then observed with the above described
140 epifluorescence microscope by the same observer, blinded to the experimental group of each
141 sample. The presence of a green acrosomal fluorescence was considered indicative of an intact
142 acrosome, whereas a partial or total absence of fluorescence was considered indicative of acrosome
143 disruption or acrosome reaction (see supplementary file, panel A).

144 **2.3.2. Immunolocalization of tyrosine-phosphorylated proteins**

145 All the procedures were carried out at room temperature unless otherwise specified.

146 Aliquots of sperm cells from the different experimental groups were spotted onto poly-L-lysine-
147 coated slides and fixed with methanol at -20° C for 15 min and with acetone for 30 sec. The slides
148 were then washed with PBS and blocked with 10% (v/v) FCS (Gibco) in PBS (blocking solution) for at
149 least 30 min. Antibody dilutions were performed in blocking solution. Monoclonal
150 antiphosphotyrosine antibody (clone 4G10, Merck Millipore, Darmstadt, Germany) was added at
151 the dilution 1:150 . Incubation was carried out overnight at 4° C. After extensive washing with PBS,
152 sperm cells were incubated with a sheep-anti-mouse FITC-conjugated secondary antibody (BioFX
153 Laboratories, Maryland, USA) for 1 h in the dark. Slides were washed with PBS and mounted with
154 Vectashield mounting medium with PI (Vector Laboratories). Control slides were treated similarly
155 with the omission of primary antiserum. Spermatozoa were evaluated with the above described
156 epifluorescence microscope.

157 Each sample was analyzed by counting at least 200 cells in order to evaluate the different positivity
158 patterns by the same observer, blinded to the experimental group of each sample.

159 Four different patterns were considered on the basis of what assessed by Bucci et al. [18] (see
160 supplementary file, panel B):

161 A: positivity in the Equatorial Subsegment (EqSS) and acrosome;

162 B: positivity in the acrosome, EqSS and principal piece of the tail;

163 C: positivity in the tail and (not constant) in the EqSS.

164 NEG: spermatozoa with no positive signal.

165

166 **2.4. Effect of TRE on in vitro fertilization (IVF)**

167 For *in vitro* fertilization trials, spermatozoa were diluted in IVF medium to obtain 750×10^3
168 spermatozoa/ml and 500 μL of the sperm suspension were placed to each well of Nunc 4-well
169 multidish. Then 45 to 50 *in vitro* matured oocytes were transferred to each well and sperm-oocyte
170 coculture was performed for 1 h in presence of TRE at the concentration of 0, 1, 10, 100 $\mu\text{g}/\text{ml}$ at
171 39°C in a humidified atmosphere of 5% CO_2 in air. The oocytes from each group were then washed
172 three times in fresh IVF medium to remove spermatozoa not bound to the zona, transferred to the
173 same medium (containing no spermatozoa) and cultured for 19 h until mounting on microscope
174 slides and fixing in acetic acid/ethanol (1 : 3) for 24 h. After staining with Lacmoid the oocytes were
175 observed under a phase-contrast microscope (total number of IVF oocytes evaluated = 665).
176 Fertilization rate (number of oocytes fertilized/ number of inseminated oocytes) and monospermy
177 rate (number of monospermic oocytes/number of fertilized oocytes) were recorded.

178

179 **2.5. Effect of TRE fractions on *in vitro* induced sperm capacitation and IVF**

180 In order to investigate the power of the fractions FA, FB, FC, FD obtained from TRE by Amberlite
181 fractionation, *in vitro* sperm capacitation and gamete coincubation during IVF were performed in
182 presence of different concentrations (0, 1, 10, 100 $\mu\text{g}/\text{ml}$) of FA, FB, FC, FD.

183 Sperm viability, acrosome integrity and tyrosine-phosphorylation of sperm proteins were evaluated
184 as above described on spermatozoa after 1 h of capacitation in presence of different concentrations
185 of the four fractions of TRE.

186 For *in vitro* fertilization assay, fertilization parameters were evaluated as above described on
187 oocytes coincubated 1h with sperm in presence of different concentrations of the four fractions of
188 TRE and then cultured 19h in fresh IVF medium until fixation (total number of IVF oocytes evaluated
189 = 3036).

190

191 **2.6 Statistical analysis**

192 Data were analyzed using R version 3.4.0. [24] Significance was set at $p < 0.05$ unless otherwise
193 specified. Results are expressed as mean \pm standard deviation. Shapiro Wilk test was applied to test
194 normality and Levene test was used to assay homogeneity of the variances for the arcsin
195 transformed variables (percentage of viable cells, percentage of acrosome integer cells; sperm
196 tyrosine phosphorylation patterns) One-way ANOVA and Tukey post hoc test were performed to
197 assess the difference between treatments. In vitro fertilization data were analyzed by a generalized
198 linear model (GLM) and a Tukey post hoc test was used to assess difference between treatments.

199

200 **3. Results**

201 **3.1. Effect of TRE on in vitro induced sperm capacitation and IVF**

202 When in vitro induced sperm capacitation was performed in presence of TRE100, sperm viability
203 was significantly higher compared with control ($p < 0.001$), TRE1 ($p < 0.001$) and TRE10 ($p < 0.05$)
204 (Fig. 1 A). Moreover, in presence of TRE100 the percentage of acrosome intact cells was higher
205 compared with control ($p < 0.05$) (Fig.1 B).

206 Tyrosine-phosphorylation of sperm proteins was significantly ($p < 0.001$) influenced by TRE: TRE10
207 induced a decrease of the percentage of cells displaying A pattern (non capacitated cells) and a
208 parallel increase of B pattern (capacitated cells) while an opposite effect of TRE100 was recorded
209 (Fig.1 C).

210 When gamete coincubation was performed in presence of TRE10 the penetration rate (number of
211 oocytes fertilized/ number of inseminated oocytes) was significantly increased ($p < 0.001$) while it
212 dramatically dropped in presence of TRE100 ($p < 0.001$). The monospermy rate (number of
213 monospermic oocytes/number of fertilized oocytes) was significantly decreased in TRE10 ($p <$
214 0.001).

215

216 **3.2. Effect of TRE fractions on in vitro induced sperm capacitation and IVF**

217 After 1 h incubation in capacitating condition, while neither FA nor FD significantly affected sperm
218 viability (Fig. 2 A, D), the percentage of viable sperm in presence of FB at the higher concentration
219 tested (100 µg/ml) was significantly ($p < 0.05$) higher compared with control and FB1 (Fig. 2 B). In
220 presence of FC100 sperm viability resulted significantly higher compared with control and FB at
221 lower concentration tested ($p < 0.05$) (Fig. 2 C)

222 Sperm acrosome integrity was not influenced by both FA and FD at all the concentration tested. In
223 presence of FB100 the percentage of acrosome intact cells was higher compared with both control
224 and FB1 ($p < 0.05$) while a significant difference between FC 100 and control was recorded ($p < 0.05$)
225 (Fig. 3).

226 Tyrosine-phosphorylation of sperm proteins was influenced by the four fractions (Fig. 4). FA and FD
227 induced a decrease of the percentage of cells displaying A pattern (non capacitated cells) and a
228 parallel increase of B pattern (capacitated cells) at the higher concentration tested (100 µg/ml) ($p <$
229 0.001) (Fig. 4 A,D). FB 10 significantly ($p < 0.001$) decreased the percentage of A pattern sperm and
230 increased the percentage of B pattern sperm while FB 100 showed an opposite effect significantly
231 decreasing the percentage of spermatozoa displaying B pattern ($p < 0.001$) (Fig. 4 B).

232 FC1 and FC100 slightly but significantly decreased the percentage of cells displaying A pattern and
233 increased the percentage of B pattern sperm ($p < 0.05$) while FC10 effect resulted more evident (p
234 < 0.001) (Fig.4 c).

235 The results on the effect of the four different TRE fractions during gamete coincubation on
236 fertilization parameters are reported in Figure 5.

237 Fraction FA did not influence fertilization parameters at all the dosages tested. FB and FC exerted a
238 diphasic effect on fertilization rate that was significantly increased at the concentration of 10 µg/ml

239 and significantly decreased at 100 µg/ml compared with control ($p < 0.001$). The monospermy rate
240 was significantly decreased in both FB10 ($p < 0.001$) and FC10 ($p < 0.05$) groups. Fraction FD was
241 effective in increasing the fertilization rate only at the concentration of 100 µg/ml.

242

243 **4. Discussion**

244 Recently some of us reported the antioxidant activity of an ethanol extract (TRE) of a commercial
245 oenological tannin (*Quercus robur* toasted oak wood, Tan'Activ R[®],TR) and its four fractions
246 obtained by fractionation on Amberlite XAD-16 [15]. It is worth noting here that in this work the
247 QR2E ethanol extract, corresponding to TRE, showed good antioxidant activity, with a SC₅₀ value of
248 6.96 µg/mL in the DPPH scavenging test. Among the XAD-16 fractions, fraction X2B, corresponding
249 to FB, showed the highest antioxidant activity, with a SC₅₀ value of 3.95 µg/mL; X2C and X2D,
250 corresponding respectively to FC and FD, showed an antioxidant activity comparable to that of the
251 QR2E extract, whereas X2A, corresponding to FA, had the lowest antioxidant activity, with a SC₅₀
252 value of 16.48 µg/mL.

253 As a first step of this study we investigated the biological effect of the ethanol extract TRE on sperm
254 capacitation, oxidative process by which male gametes acquire the ability to fertilize oocytes
255 [1,4,25]. One of the early events occurring during sperm capacitation is the production of low levels
256 ROS that exert a positive role in the molecular mechanism regulating the process of capacitation
257 [3,6].

258 The treatment of spermatozoa with TRE at the higher concentration tested (100 µg/ml) during 1 h
259 culture under in vitro capacitating conditions exerted an inhibitory effect on sperm capacitation on
260 the basis of the results obtained on tyrosine phosphorylation of sperm proteins, process shown to
261 be highly related with the capacitation process [18,26]. The inhibitory effect induced by TRE100

262 agree well with the observation that tyrosine phosphorylation events associated with sperm
263 capacitation could be reversed by antioxidants such as catalase and ascorbic acid [2,27-29].
264 Interestingly TRE at the concentration of 10 $\mu\text{g}/\text{ml}$ stimulated the process of capacitation as it
265 increased the percentage of spermatozoa with a positivity of tail principal piece (B pattern) [18]. It
266 has been demonstrated that moderate and controlled amounts of ROS exert a positive influence on
267 tyrosine phosphorylation during capacitation through their ability to enhance intracellular levels of
268 cAMP and inhibit phosphatase activity [2,25,28,30-32]. Therefore we can hypothesize that during in
269 vitro induction of sperm capacitation TRE at low concentration (10 $\mu\text{g}/\text{ml}$) was able to maintain the
270 amount of ROS at low levels leading to a positive influence on tyrosine phosphorylation while higher
271 concentration of TRE, reducing ROS production, prevented phosphorylation events associated with
272 sperm capacitation.

273 TRE, only at the higher concentration tested (100 $\mu\text{g}/\text{ml}$), exerted a positive effect on the percentage
274 of live cells after 1 h culture in capacitating conditions. It has to be taken into account that a decrease
275 in sperm viability is normally associated with in vitro sperm capacitation process [33] and that
276 capacitation and apoptosis are considered part of a redox-regulated continuum [34]. In fact the fine
277 balance between ROS production and scavenging as well as the right timing for ROS production are
278 of fundamental importance for the acquisition of fertilizing ability by spermatozoa as when the
279 intrinsic generation of ROS overwhelms the limited capacity of these cells to protect themselves
280 against oxidative attack, oxidative stress cause sperm senescence leading to cell death [7,25,34]. In
281 this view TRE100, by inhibiting the capacitation process, reduced the physiological drop in sperm
282 viability under capacitating condition. In our experiment in fact the percentage of viable cells
283 decreased from 83,4% in fresh semen to 35,4% after 1h in vitro capacitation in control group while
284 TRE100 maintained the percentage of sperm with intact plasma membrane to higher levels (66,9%).

285 The inhibitory effect of TRE100 on sperm capacitation is further confirmed by the reduction of
286 spontaneous acrosomal loss naturally occurring in a low rate during in vitro capacitation [35].

287 As the capacitation is the process that enables spermatozoa to gain the ability to bind to the zona
288 pellucida, penetrate it and finally fuse with the oocyte, in order to fully evaluate the biological effect
289 of TRE on sperm functions, in vitro fertilization tests in presence of different concentrations of TRE
290 were performed. According with the results obtained on capacitation parameters, TRE10 increased
291 oocyte fertilization rate that was, on the contrary, strongly inhibited by TRE100 confirming the
292 powerful biological ability of TRE to modulate in a dose dependent biphasic manner the capacitation
293 process.

294 The reduction of monospermy rate (number of monospermic oocytes/number of fertilized oocytes)
295 recorded in TRE10 was due to well known reduced ability of in vitro matured pig oocyte to efficiently
296 block polyspermy [36]: TRE10, stimulating sperm capacitation, increased the penetration rate
297 parallely increasing polyspermy in fertilized oocytes, 77% of whom contained more than one
298 sperm head/male pronucleus.

299 The four fraction of TRE obtained by Amberlite XAD-16 fractionation (FA, FB, FC, FD) were also
300 tested in order to assess their effect on boar sperm capacitation and fertilizing ability.

301 The results obtained on tyrosine phosphorylation of sperm protein suggest that FB, the fraction with
302 the highest antioxidant activity [15], is the most potent fraction exerting, similarly to TRE, a
303 stimulatory effect of sperm capacitation at 10 µg/ml and an inhibitory effect at 100 µg/ml. FB
304 resulted less powerful as it stimulated capacitation at 10 µg/ml but did not reduce the percentage
305 of capacitated sperm compared to control at the highest dose tested (100 µg/ml). FD and, in a lesser
306 extent, FA were effective in stimulating capacitation only at the concentration of 100 µg/ml. The
307 inhibiting effect on sperm capacitation of FB100 was confirmed, for the reasons previously
308 discussed, by the higher viability and acrosome integrity observed when in vitro sperm capacitation

309 was performed in presence of this fraction at the higher concentration. The results of in vitro
310 fertilization assay confirm the different activity of the four fractions: FB and FC exerted a biphasic
311 effect (stimulatory at 10 µg/ml and inhibitory at 100 µg/ml) on oocyte fertilization rate, FD increased
312 the fertilization rate only at the higher concentration tested (100 µg/ml) while FA was ineffective.
313 On these bases, the potency of the four fractions seems to be highest in FB followed by FC, faint in
314 FD and nearly absent in FA. Our results agree well with those reported by Muccilli et al. [15] for the
315 radical scavenging activity of the four fractions (see above), supporting the hypothesis that their
316 different antioxidant activity have a role in their action on sperm capacitation. In fact, for example,
317 Muccilli et al. [15] observed the highest antioxidant activity in fraction FB.
318 To our knowledge, the results of this study represent the first evaluation of biological activities of
319 an ethanol extract of an oenological commercial oak-derived tannin and its fractions during the
320 redox-regulated process of capacitation that make the spermatozoon competent of fertilizing the
321 oocyte. TRE and its fraction (in a different extent) exerted a powerful biological effect in finely
322 modulating capacitation and in turn sperm fertilizing ability. Which of constituents is responsible for
323 the biological activity recorded has not yet been established, although Muccilli et al. [15] identified
324 known polyphenols as major constituents of fraction X2B (FB in the present work), namely a
325 monogalloyl glucose isomer (MW = 332.2), glucose esterified by hexahydroxydiphenic acid (HHDP)
326 (MW = 482.2), gallic acid (MW = 170.1), and the ellagitannins castalin (MW = 632.4), vescalagin (MW
327 = 934.6) and grandinin (or its isomer roburin E) (MW = 1066.7). However, the effects exerted appear
328 to be of interest and worth of a deeper investigation.

329

330

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333

334 *The authors have declared no conflicts of interest.*

335 **5. References**

- 336 [1] Yanagimachi R. Mammalian fertilization. In: Knobil E, Neill D, editors. *The Physiology of*
337 *Reproduction*, Raven Press, New York; 1994, p. 189–318.
- 338 [2] Ecroyd HW, Jones RC, Aitken RJ. Endogenous redox activity in mouse spermatozoa and its role in
339 regulating the tyrosine phosphorylation events associated with sperm capacitation. *Biol Reprod*
340 2003; 69:347–54.
- 341 [3] de Lamirande E, O’Flaherty C. Sperm capacitation as an oxidative event. In: Aitken J, Alvarez J,
342 Agawar A, editors. *Studies on Men Health and Fertility, Oxidative Stress in Applied Basic*
343 *Research and Clinical Practice*, Springer Science Business Media, New York; 2012, p. 57–94.
- 344 [4] de Lamirande E, Gagnon C. Human sperm hyperactivation and capacitation as parts of an
345 oxidative process. *Free Radic Biol Med* 1993;14:157–66.
- 346 [5] O’Flaherty C, de Lamirande E, Gagnon C. Reactive oxygen species and protein kinases modulate
347 the level of phospho-MEK-like proteins during human sperm capacitation. *Biol Reprod*
348 2005;73:94–105.
- 349 [6] Aitken RJ, Nixon B. Sperm capacitation: a distant landscape glimpsed but unexplored. *Mol Hum*
350 *Reprod* 2013;19:785–93.
- 351 [7] de Lamirande E, Leclerc P, Gagnon C. Capacitation as a regulatory event that primes spermatozoa
352 for the acrosome reaction and fertilization. *Mol Hum Reprod* 1997;3:175–94.
- 353 [8] Agarwal A, Durairajanayagam D, du Plessis SS. Utility of antioxidants during assisted
354 reproductive techniques: an evidence based review. *Reprod Biol Endocrinol* 2014; 112.
- 355 [9] Kolečkar V, Kubikova K, Rehakova Z, Kuca K, Jun D, Jahodar L, Opletal L. Condensed and
356 hydrolysable tannins as antioxidants influencing the health. *Mini Rev Med Chem* 2008;8(5):436-
357 47.

- 358 [10] Okuda T, Ito H. Tannins of Constant Structure in Medicinal and Food Plants—Hydrolyzable
359 Tannins and Polyphenols Related to Tannins. *Molecules* 2011;16: 2191-217.
- 360 [11] Martinez JP, Sasse F, Brönstrup M, Diez J, Meyerhans A. Antiviral drug discovery: broad-spectrum
361 drugs from nature. *Nat Prod Rep* 2015;32:29-48.
- 362 [12] Zhang B, Cai J, Duan CQ, Reeves MJ, He F. A review of polyphenolics in oak woods. *Int J Mol Sci*
363 2015;16(4):6978-7014.
- 364 [13] Chatonnet P, Dubourdieu D. Comparative study of the characteristics of American white oak
365 (*Quercus alba*) and European oak (*Quercus petraea* and *Q. robur*) for production of barrels used
366 in barrel aging of wines. *American Journal of Enology and Viticulture* 1998;49(1):79–85.
- 367 [14] Versari A, du Toit W, Parpinello GP. Oenological tannins: a review. *Australian Journal of Grape*
368 *and Wine Research* 2013;19:1–10.
- 369 [15] Muccilli V, Cardullo N, Spatafora C, Cunsolo V, Tringali C. α -Glucosidase inhibition and
370 antioxidant activity of an oenological commercial tannin. Extraction, fractionation and analysis
371 by HPLC/ESI-MS/MS and (1)H NMR. *Food Chem* 2017;215: 50-60.
- 372 [16] Spinaci M, Volpe S, De Ambrogi M, Tamanini C, Galeati G. Effects of epigallocatechin-3-gallate
373 (EGCG) on in vitro maturation and fertilization of porcine oocytes. *Theriogenology*. 2008
374 15;69(7):877-85.
- 375 [17] Spinaci M, Chlapanidas T, Bucci D, Vallorani C, Perteghella S, Lucconi G, Communod R, Vigo D,
376 Galeati G, Faustini M, Torre ML. Encapsulation of sex sorted boar semen: sperm membrane
377 status and oocyte penetration parameters. *Theriogenology* 2013;79(4):575-81.
- 378 [18] Bucci D, Galeati G, Tamanini C, Vallorani C, Rodriguez-Gil JE, Spinaci M. Effect of sex sorting on
379 CTC staining, actin cytoskeleton and tyrosine phosphorylation in bull and boar spermatozoa.
380 *Theriogenology* 2012;77:1206–16.

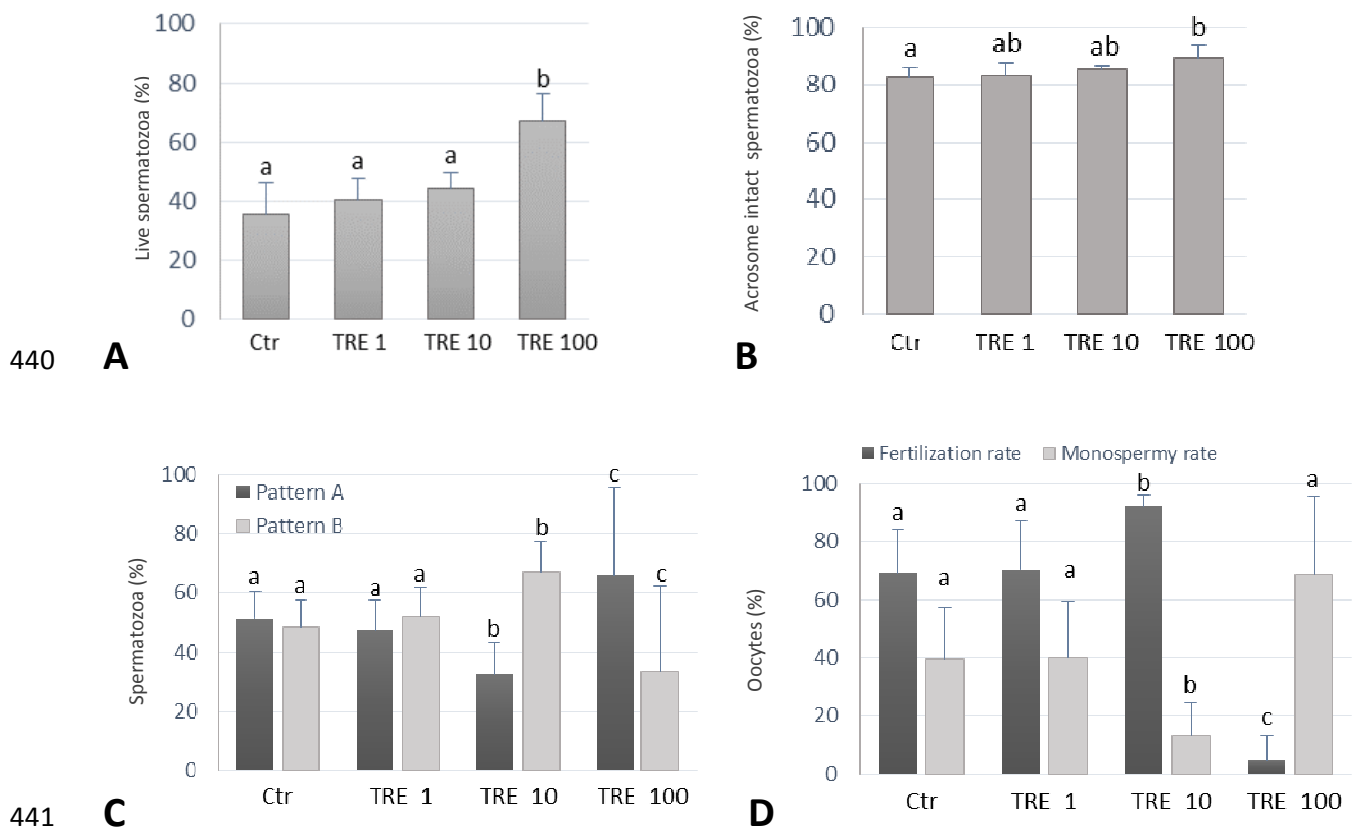
- 381 [19] Gadani B, Bucci D, Spinaci M, Tamanini C, Galeati G. Resveratrol and Epigallocatechin-3-gallate
382 addition to thawed boar sperm improves in vitro fertilization. *Theriogenology* 2017;90:88-93.
- 383 [20] Spinaci M, Bucci D, Gadani B, Porcu E, Tamanini C, Galeati G. Pig sperm preincubation and
384 gamete coincubation with glutamate enhance sperm-oocyte binding and in vitro fertilization.
385 *Theriogenology* 2017;95:149-53.
- 386 [21] Petters RM, Wells KD. Culture of pig embryos. *J Reprod Fertil* 1993;48:61-73.
- 387 [22] Funahashi H, Cantley T, Day BN. Synchronization of meiosis in porcine oocytes by exposure to
388 dibutyl cyclic adenosine monophosphate improves developmental competence following in
389 vitro fertilization. *Biol Reprod* 1997; 57:49–53.
- 390 [23] Brackett BG, Oliphant G. Capacitation of rabbit spermatozoa in vitro. *Biol Reprod* 1975;12:260-
391 74.
- 392 [24] R Core Team. R: A Language and Environment for Statistical Computing. Vienna, Austria: R
393 Foundation for Statistical Computing, 2017.
- 394 [25] Aitken RJ, Baker MA, Nixon B. Are sperm capacitation and apoptosis the opposite ends of a
395 continuum driven by oxidative stress? *Asian J Androl* 2015;17(4):633-9.
- 396 [26] Visconti PE, Stewart-Savage J, Blasco A, Battaglia L, Miranda P, Kopf GS, Tezón JG. Roles of
397 bicarbonate, cAMP, and protein tyrosine phosphorylation on capacitation and the spontaneous
398 acrosome reaction of hamster sperm. *Biol Reprod* 1999;61:76-84.
- 399 [27] Aitken RJ, Paterson M, Fisher H, Buckingham DW, van Duin M. Redox regulation of tyrosine
400 phosphorylation in human spermatozoa and its role in the control of human sperm function. *J*
401 *Cell Sci* 1995;108:2017-2025.
- 402 [28] Aitken RJ, Harkiss D, Knox W, Paterson M, Irvine DS. A novel signal transduction cascade in
403 capacitating human spermatozoa characterised by a redox-regulated, cAMP-mediated
404 induction of tyrosine phosphorylation. *J Cell Sci* 1998;111:645–56.

- 405 [29] Donà G, Fiore C, Tibaldi E, Frezzato F, Andrisani A, Ambrosini G, Fiorentin D, Armanini D, Bordin
406 L, Clari G. Endogenous reactive oxygen species content and modulation of tyrosine
407 phosphorylation during sperm capacitation. *Int J Androl* 2011;34:411-9.
- 408 [30] Lewis B, Aitken RJ. A redox-regulated tyrosine phosphorylation cascade in rat spermatozoa. *J*
409 *Androl* 2001;22: 611–22.
- 410 [31] Rivlin J, Mendel J, Rubinstein S, Etkovitz N, Breitbart H. Role of hydrogen peroxide in sperm
411 capacitation and acrosome reaction. *Biol Reprod* 2004;70: 518–22.
- 412 [32] Baumber J, Sabeur K, Vo A, Ball BA. Reactive oxygen species promote tyrosine phosphorylation
413 and capacitation in equine spermatozoa. *Theriogenology* 2003; 60: 1239–47.
- 414
- 415 [33] Ramió-Lluch L, Yeste M, Fernández-Novell JM, Estrada E, Rocha L, Cebrián-Pérez JA, Muiño-
416 Blanco T, Concha II, Ramírez A, Rodríguez-Gil JE. Oligomycin A-induced inhibition of
417 mitochondrial ATP-synthase activity suppresses boar sperm motility and in vitro capacitation
418 achievement without modifying overall sperm energy levels. *Reprod Fertil Dev* 2014;26(6):883-
419 97.
- 420 [34] Aitken RJ. The capacitation-apoptosis highway: oxysterols and mammalian sperm function. *Biol*
421 *Reprod.* 2011;85(1):9-12.
- 422 [35] Fénichel P, Donzeau M, Farahifar D, Basteris B, Ayraud N, Hsi BL. Dynamics of human sperm
423 acrosome reaction: relation with in vitro fertilization. *Fertil Steril* 1991;55(5):994-9.
- 424 [36] Funahashi H. Polyspermic penetration in porcine IVM-IVF systems. *Reprod Fertil Dev*
425 2003;15(3):167-77.

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428 Fig. 1. Effect of TRE at concentrations of 0, 1, 10, 100 $\mu\text{g/ml}$ during capacitation and gamete
 429 coincubation. (A) Sperm viability, (B) percentage of acrosome intact spermatozoa and (C)
 430 percentage of sperm cells displaying tyrosine-phosphorylation of sperm proteins typical of either
 431 non capacitated cells (pattern A) or capacitated cells (pattern B) after 1 h sperm incubation in
 432 capacitating condition in presence of different concentrations of TRE. (D) Fertilization rate (number
 433 of oocytes fertilized/ number of inseminated oocytes) and monospermy spermy rate (number of
 434 monospermic oocytes/number of fertilized oocytes) after 1h gamete coincubation in presence of
 435 different concentrations of TRE. Data represent the mean \pm SD of 5 replicates for sperm viability,
 436 acrosome integrity and IVF and 4 replicates for immunolocalization of sperm phosphotyrosine,
 437 repeated in different experiments. Different letters on the same bar type represent significant
 438 difference for $P < 0.05$ between treatments.

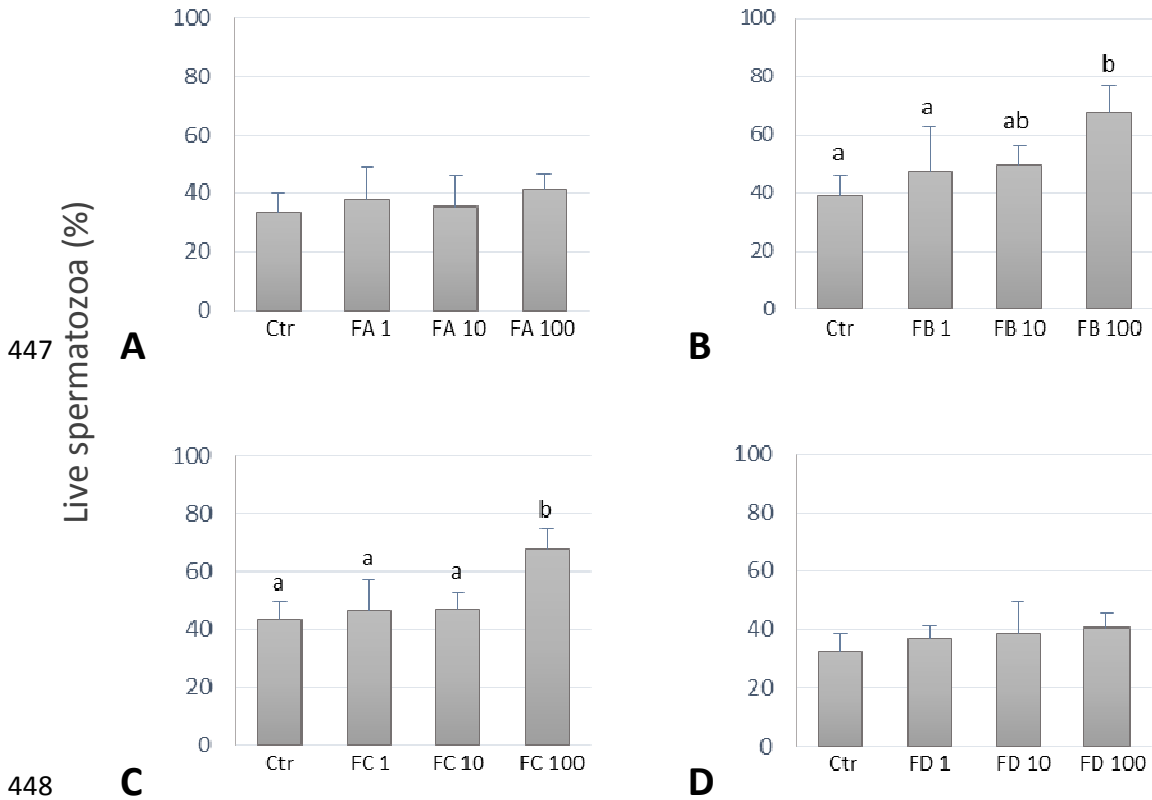
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442 Fig. 2. Effect of fractions FA (panel A), FB (panel B), FC (panel C), FD (panel D) at concentrations of
443 0, 1, 10, 100 µg/ml during 1 h sperm incubation in capacitating condition on sperm viability.
444 Data represent the mean ± SD of 5 replicates repeated in different experiments. Different letters
445 represent significant difference for P < 0.05 between treatments.

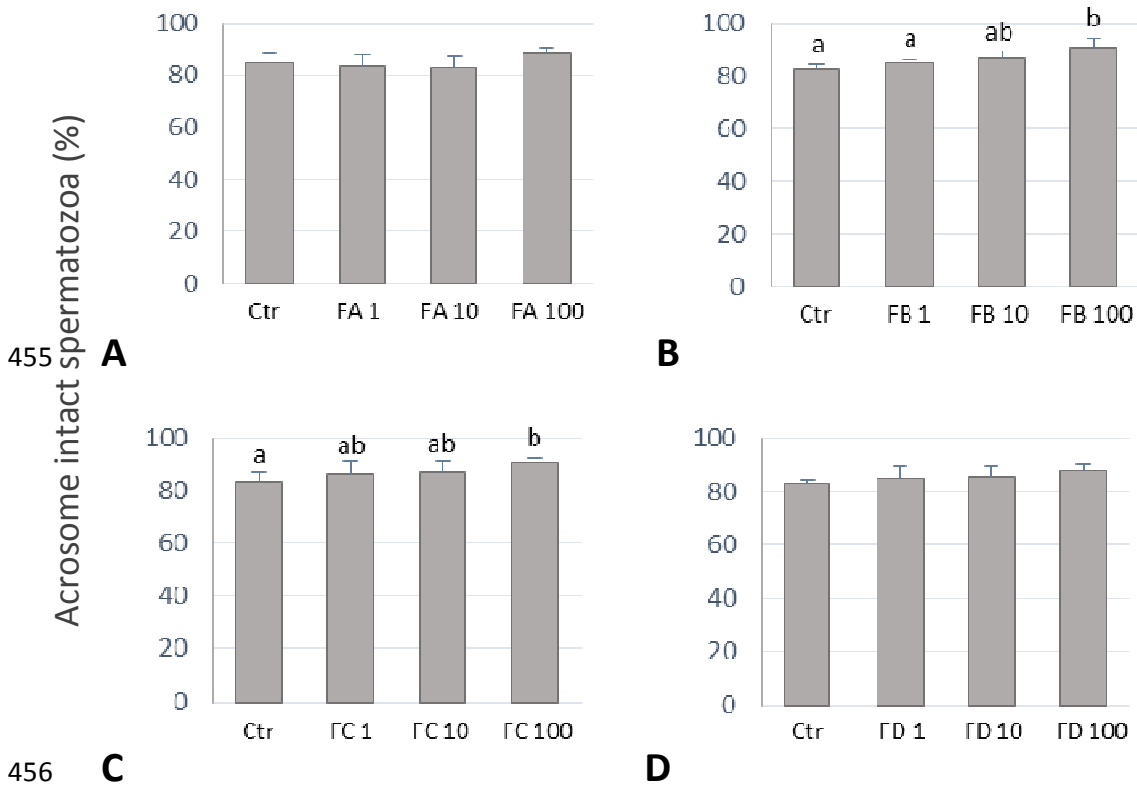
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449 Fig. 3. Effect of fractions FA (panel A), FB (panel B), FC (panel C), FD (panel D) at concentrations of
450 0, 1, 10, 100 $\mu\text{g/ml}$ during 1 h sperm incubation in capacitating condition on sperm acrosome
451 integrity.

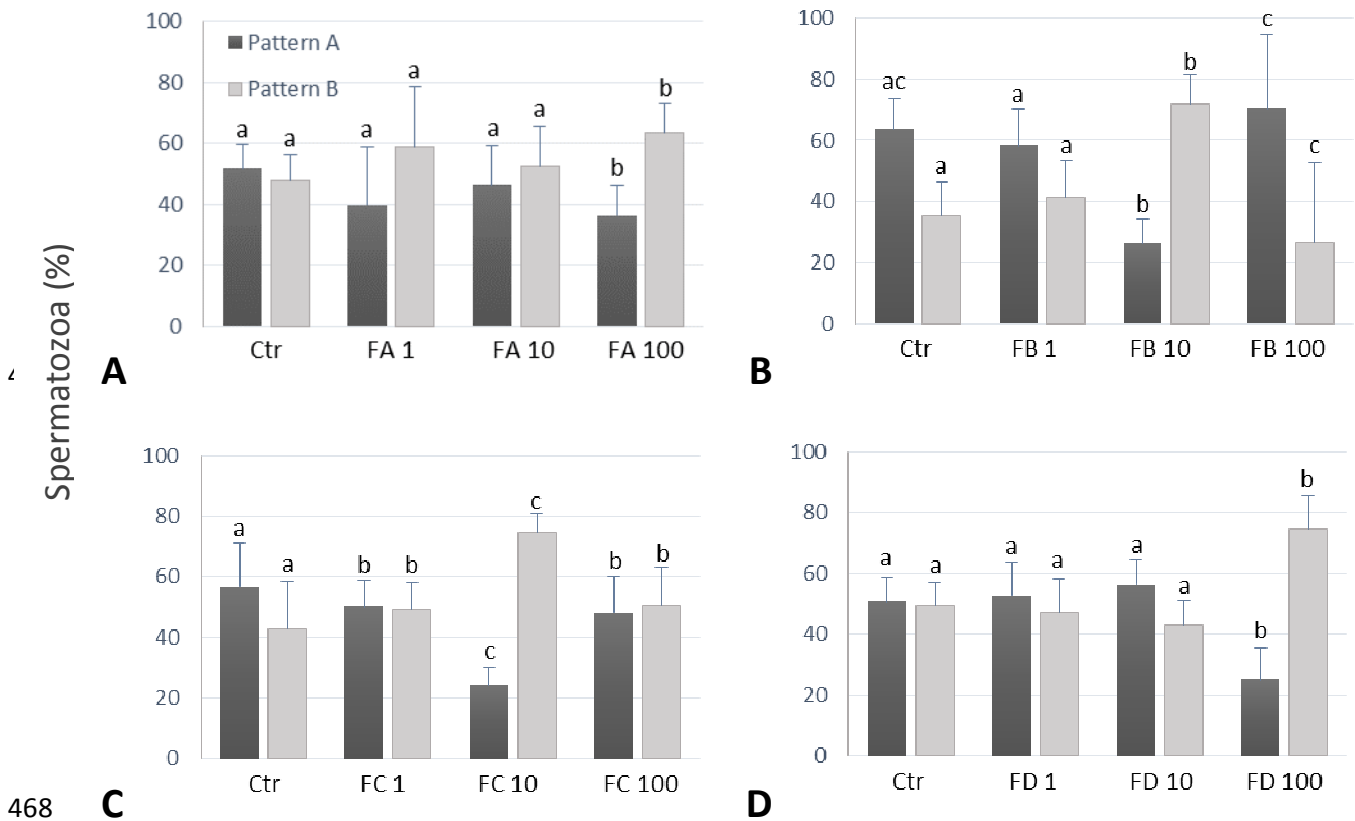
452 Data represent the mean \pm SD of 5 replicates repeated in different experiments. Different letters
453 represent significant difference for $P < 0.05$ between treatments.

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458 Fig.4. Effect of fractions FA (panel A), FB (panel B), FC (panel C), FD (panel D) at concentrations of 0,
 459 1, 10, 100 $\mu\text{g/ml}$ during 1 h sperm incubation in capacitating condition on tyrosine-phosphorylation
 460 of sperm proteins: pattern A typical of non capacitated cells (positivity in the EqSS and acrosome);
 461 pattern B typical of capacitated cells (positivity in the acrosome, EqSS and principal piece of the
 462 tail).
 463 Data represent the mean \pm SD of 4 replicates repeated in different experiments.
 464 Different letters on the same bar type represent significant difference for $P < 0.05$ between
 465 treatments.

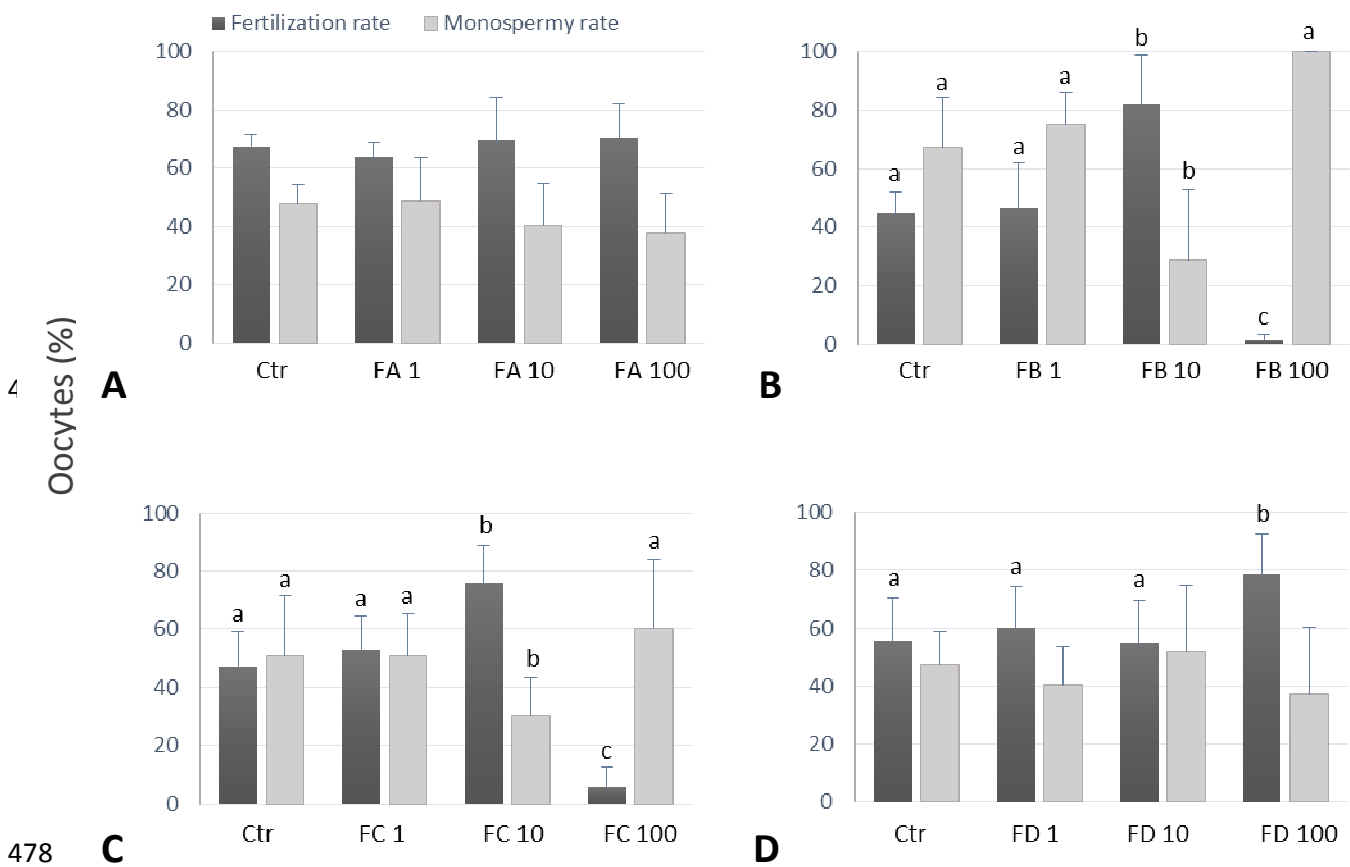
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470 Fig. 5. Effect fractions FA (panel A), FB (panel B), FC (panel C), FD (panel D) at concentrations of 0, 1,
 471 10, 100 $\mu\text{g/ml}$ during 1h gamete coincubation on fertilization parameters: fertilization rate (number
 472 of oocytes fertilized/ number of inseminated oocytes) and monospermy rate (number of
 473 monospermic oocytes/number of fertilized oocytes).
 474 Data represent the mean \pm SD of 5 replicates repeated in different experiments.
 475 Different letters on the same bar type represent significant difference for $P < 0.05$ between
 476 treatments.



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