Snake venoms as a source of compounds modulating sperm physiology: Secreted phospholipases A2 from Oxyuranus scutellatus scutellatus impact sperm motility, acrosome reaction and in vitro fertilization in mice.

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ABSTRACT

The goal of this study was to identify new compounds from venoms able to modulate sperm physiology and more particularly sperm motility. For this purpose, we screened the effects of 16 snake venoms cleared of molecules higher than 15 kDa on sperm motility. Venoms rich in neurotoxins like those from *Oxyuranus scutellatus scutellatus* or *Daboia russellii*, were highly potent inhibitors of sperm motility. In contrast, venoms rich in myotoxins like those from *Echis carinatus*, *Bothrops alternatus* and *Macrovipera lebetina*, were inactive. From the main pharmacologically-active fraction of the Taipan snake *Oxyuranus scutellatus s.*, a proteomic approach allowed us to identify 16 different proteins, among which OS1 and OS2, two secreted phospholipases A2 ($sPLA_2$). Purified OS1 and OS2 mimicked the inhibitory effect on sperm motility and were likely responsible for the inhibitory effect of the active fraction. OS1 and OS2 triggered sperm acrosome reaction and induced lipid rearrangements of the plasma membrane. The catalytic activity of OS2 was required to modulate sperm physiology since catalytically inactive mutants had no effect. Finally, sperm treated with OS2 were less competent than control sperm to initiate *in vitro* normal embryo development. This is the first report characterizing $sPLA_2$ toxins that modulate *in vitro* sperm physiology.

1. Introduction

Human fecundity has been decreasing for several decades and it is becoming a major problem in modern society [1]. This decline is first likely due to a societal cause, related to the postponed decision of first pregnancy, and second to an environmental cause related to the increased levels of pollutants, and in particular of endocrine disruptors which might interfere directly with gametogenesis [2]. Infertility treatment is hampered by our incomplete knowledge of sperm physiology and fertilization, especially at the molecular level. To unravel the mechanisms underlying the reduction of reproductive fitness, one can identify the genes involved in gametogenesis through the study of infertile couples and animals models [3-5] or analyze the effects of various compounds having specific functions. The molecular pathways and the different proteins involved in the three main physiological functions of mature sperm occurring in the female tract that are sperm motility, capacitation and acrosome reaction are still subjects of intensive research [6, 7]. Discovering new molecular pathways and/or proteins involved in the control of sperm physiology is a necessity. Different strategies including gene targeting and proteomic analyses have been used to identify the molecular mechanisms of sperm physiology like invalidating genes or performing proteomic analyses. Another strategy is based on the use of very specific inhibitors of a sperm function, and the purification of the targeted protein by using the inhibitor as a bait. This strategy has been very successful in the ion channels field. For instance, the plant alkaloid ryanodine allowed the characterization of a Ca^{2+}channel from the endoplasmic reticulum while dihydropyridines allowed the characterization of another Ca^{2+}channel from T tubules of the skeletal fibers [8]. In sperm, a similar approach using a specific sperm antibody allowed the characterization of Izumo, a unique protein involved in sperm-oocyte binding [9].

Venoms have also been used as a major source of biological active molecules to provide key tools to purify and characterize new mammalian proteins. For instance, apamin from bee venom has allowed to characterize a Ca^{2+}-activated K^{+}-channel [10]. Several types of molecules are present in venoms, including proteins, peptides and polyamines, and more than hundred compounds can be found in a single venom. Most venom compounds are highly specific. Such high specificity can be illustrated by the property of the spider toxin ω-AgaIVA that distinguishes between two spliced variants of Ca^{2+} channels. Indeed, ω-AgaIVA inhibits P-type but not Q-type Ca^{2+} channels, while these channels result from the alternative splicing of the *Cacna1a* gene [11]. The specificity of venom compounds is also illustrated by the fact that venom toxins or compounds structurally close to them are used as drugs in the treatment of pain, neurological diseases, cancers or autoimmune diseases [12]. Because of the diversity and specificity of venom compounds, we undertook a wide screening of various snake venoms in order to characterize new biologically active compounds acting on sperm functions.

In this paper, we screened on sperm motility 16 different snake venoms belonging to *Elapidae*, *Viperidae* and *Colubridae* families. Crude venoms were first fractionated by gel filtration to remove proteases, and fractions with molecular masses lower than 15 kDa were tested. Most venoms were potent inhibitors of sperm motility except those from *Echis carinatus*, *Bothrops alternatus* and *Macrovipera lebetina*. The two most potent venoms were those from *Oxyuranus scutellatus scutellatus* and *Daboia russellii*. We then focused on the most potent inhibiting fraction from *Oxyuranus scutellatus scutellatus*. By a proteomic analysis, we demonstrated that this fraction is enriched in secreted phospholipases A_2 ($sPLA_2$), in particular OS1 and OS2, two snake $sPLA_2$ with different toxicological and pharmacological properties [13]. We thus tested the effects of recombinant OS1, OS2 as well as of mutant proteins having different levels of enzymatic activities on sperm motility, sperm

acrosome reaction (AR), and *in vitro* fertilization (IVF). We found that recombinant OS1 and OS2 $sPLA_2$s were potent inhibitors of sperm motility while they were potent activators of acrosome reaction. *In vitro* fertilization experiments indicate that embryos obtained with OS2-treated sperm showed an impaired development, suggesting that sperm lipid metabolism is important for the fertilizing potential of sperm.

2. Materials and methods

2.1. Venom separation

Venoms were obtained from Latoxan, SA (Valence, France). Hundred mg of crude venom was dissolved in 1 ml of 100 mM ammonium acetate pH 6.8 and centrifugated at 10,000 g for 10 min. Two hundred fifty µl of supernatant was used for purification by gel filtration. Separation was performed on a Superdex^{TM} peptide 10/300 GL gel filtration column with elution at 0.5 ml/min in 100 mM ammonium acetate pH 6.8. Fractions of 500 µL were frozen after collection before subsequent assays. Fractions with molecular masses higher than 15 kDa were discarded (fraction A1 to A8). For screening, we first pooled fractions A9-B4 to test the overall activity. The pooled fractions were prepared by mixing 100 µL of fractions A9 to B4, followed by lyophilization and solubilization in 120 µL of M16 medium.

2.2. Computer-assisted motility analysis

All protocols have been reviewed and approved by the local ethical committee. OF1 male mice were 2-6 months old (Charles River, France). Sperm from caudae epididymides were allowed to swim in 1 ml of M2 medium for 10 min. Sperm was resuspended in M16 and incubated with venom fractions at 37°C for 10 min (237.5 µL of sperm were mixed with 12.5 µL of a fraction). After incubation, the sperm suspension was immediately placed onto an analysis chamber (2X-CEL Slides, 100 µm depth, Leja Products B.V., Netherlands) and kept at 37 °C for microscopic quantitative study of sperm movement. Sperm motility parameters were measured at 37°C using a sperm analyzer (Hamilton Thorn Research, Beverley). The settings employed for analysis were as follows: acquisition rate: 60 Hz; number of frames: 100; minimum contrast: 25; minimum cell size: 10; low static-size gate: 2.4; high static-size gate: 2.4; low static-intensity gate: 1.02; high static-intensity gate: 1.37 ; minimum elongation

gate: 12; maximum elongation gate: 100; magnification factor: 0.70. The motility parameters measured were curvilinear velocity (VCL) and amplitude of lateral head displacement (ALH). A minimum of 100 motile spermatozoa were analyzed for each assay.

2.3. Proteomic analysis

In order to increase the sequence coverage of identified proteins, three experiments were performed with two distinct chromatographic gradients and three methods of mass spectrometry. Protein samples (experiment 1 and 2: 21 µL, experiment 3: 10 µL) were dried by vacuum centrifugation and resuspended in 50 mM ammonium bicarbonate (pH 8), denatured with 2% sodium dodecyl sulfate, reduced with 45 mM dithiothreitol (50°C for 30 min) and alkylated with 100 mM iodoacetamide at room temperature for 40 min. The protein mixture was then digested by addition of a trypsin solution (Porcine modified, Promega) at 1:20 (experiments 1 and 2) or 3:20 (experiment 3) ratio (w/w), and incubated overnight at 37°C. Protein digests were dried by vacuum centrifugation and resuspended in 20 µL of buffer A (2% acetonitrile in water with 0.05% TFA). Three µL of the resulting sample were first loaded onto a trap column (PepMap100 C18, 5 µm, 100 Å, 300 µm i.d. x 5 mm, Dionex Corporation) for desalting and concentration, and then back-eluted onto the column (PepMap100 C18, 3 µm, 100 Å, 75 µm i.d. x 15 cm, Dionex Corporation). The flow rate through the column was set to 300 nL/min. Mobile phase buffers were: A = 2% acetonitrile in water with 0.05% TFA and B = 80% acetonitrile in water with 0.04% TFA. Peptides were separated using the following gradient: (i) experiments 1 and 3: 0-5 min: 0-10% B (v/v), 5-45 min: 10-42% B (v/v), 45-55 min: 42-58% B (v/v), 55-65 min 90% B (v/v) and then re-equilibrated :65-80 min 100% A (v/v); (ii) experiment 2: 0-5 min: 0-10% B (v/v), 5-40 min 10-42% B (v/v), 40-55 min 42-90% B (v/v), 55-70 min 90% B (v/v) and then re-equilibrated :70-85 min 100% A (v/v). The eluent was spotted directly onto a MALDI target plate

(Applied Biosystems) using a Probot Microfraction Collector (Dionex Corporation). The eluent was mixed 1:3 (v/v) post-column with 2 mg/mL HCCA in 70% acetonitrile and 0.1% TFA. Mass spectrometry analyses were performed on a 4800 MALDI-TOF/TOF instrument (Applied Biosystems). The instrument was operated in positive ion mode and externally calibrated. MS spectra were acquired over a mass range of 750-3500 m/z. For each sample spot, a maximum of 20 precursors with S/N over 50 were selected for fragmentation, starting with the strongest (experiments 1 and 3) or weakest (experiment 2) precursor. MS/MS spectra were collected at the most intense point of the chromatographic elution profile, using air as the collision gas and a collision energy of 1 kV. For protein identification, all MS/MS data obtained (experiments 1, 2 and 3) were submitted to Protein Pilot 2.0.1 software program (Applied Biosystems) using the Paragon protein database search algorithm [14], with trypsin as the digestion agent, cystein modification by iodoacetamide and Rapid ID as search effort. Searches were performed against the NCBI protein database (update 05-10-2009), limited to *Oxyuranus scutellatus* sequences. Only proteins identified with at least a confidence of 95%, or a ProtScore of 1.3, were reported.

2.4. Production of recombinant sPLA$_2$

Native OS1 and OS2 sPLA$_2$s from *Oxyuranus scutellatus scutellatus* (Taipan) snake venom and native Ba-II and Ba-IV K-49 sPLA$_2$-like proteins from *Bothrops asper* venom were purified as described [15, 16]. Recombinant wild-type OS2 and its catalytically-inactive mutants were prepared and purified to homogeneity as described previously [13]. We did not observe any potency differences between native and recombinant enzymes and results obtained with both types of protein were pooled.

2.5. Acrosome reaction assay

Sperm from caudae epididymes of OF1 mice were allowed to swim in M2 medium for 10 min. For $sPLA_2$ treatment, sperm were incubated with $sPLA_2$ in M16 medium at 37°C for the last 10 min. Sperm were then transferred to PBS solution and fixed with 4% paraformaldehyde for 2 min. Sperm were washed with 100 mM ammonium acetate pH 6.8 for 2 min, wet-mounted on slides and allowed to air dry. Slides were rinsed with water, stained with Coomassie blue (0.22%) for 2 min and finally rinsed with water. Slides were counted immediately and at least 150 sperm cells were scored per slide.

2.6. Confocal microscopy

Control untreated sperm (non capacitated) or sperm treated for 10 min with 200 nM OS2 in M16 medium were washed twice with PBS, and then incubated in a staining buffer (from Apoptosis detection kit-Sigma Aldrich, France) containing both carboxyfluorescein diacetate (6-CFDA) and 1 µg/mL annexin V-Cy3 for 15 min in the dark at room temperature. After incubation with annexin V-Cy3, sperm was washed twice with the staining buffer and fixed in 4% paraformaldehyde. Annexin-V staining was analyzed using a confocal microscope (Leica).

2.7. Chemical compounds

M2, M16 medium and Apoptosis detection kit were purchased from Sigma.

2.8. Statistical analyses

Statistical analyses were performed with SigmaPlot. T-test and paired t-test were used to compare the effects of various compounds on AR and fertility, respectively. Data represent mean ± SEM. Statistical tests with a p values ≤ 0.05 were considered as statistically significant.

3. Results

3.1 Venom sPLA$_2$s inhibit sperm motility

Our main goal was to identify compounds from venoms able to modulate sperm physiology and more particularly sperm motility. We used a CASA system (Computer Assisted Sperm Analysis) to test the effects of venom fractions on sperm motility. We focused more particularly on two sperm motility parameters, the VCL corresponding to Curvilinear Velocity (microns/sec) and the ALH corresponding to Amplitude of Lateral Head Displacement (microns). We tested on sperm motility 16 different snake venoms from *Elapidae*, *Crotalidae* and *Colubridae* families that originate from different continents (South and North America, Asia and Africa). The venoms were first fractionated by size exclusion chromatography and fractions containing large proteins such as proteases were discarded (Fig. 1A). Fractions containing proteins higher than 15 kDa were identified by calibrating the gel filtration column with protein standards (cytochrome C, aprotinin and vitamin B12). A gel analysis with Coomassie staining was performed to check that proteins above 15 kDa were absent from the fractions of interest (not shown). Second, a two-step screening protocol was developed to test the venom fractions. First, we tested all collected fractions below 15 kDa from one venom as a single pool. Second, we focused on the most inhibiting venoms and tested individually the different collected fractions. Fig. 1B presents the effects of the 16 tested venoms on non capacitated sperm incubated during 10 min with the pooled fractions (A9-B4) from the different venoms. *Daboia russellii* and *Oxyuranus scutellatus scutellatus* venoms were particularly potent and decreased sperm VCL by around 50%. On the other hand, *Echis carinatus*, *Bothrops alternatus* and *Macrovipera lebetina* venoms were inactive. The other venoms presented intermediate activities on sperm motility. To identify the compounds involved in the decrease of motility, we then tested individually the fractions from

Oxyuranus scutellatus scutellatus. Fraction A9 consisting of compounds with the highest molecular masses (10-15 kDa) was the most potent and decreased sperm VCL by more than 30% (Fig. 1C). We then analyzed the composition of fraction A9 by a proteomic approach. Sixteen non-redundant proteins were identified with a confidence of at least 95% (Table 1). Redundancy between proteins identified was minimized using a grouping function, which assigned an "unused score" to the peptides that are unique to a protein or group of redundant proteins. For example, OS2 is a competitor protein of PLA-7 precursor because it contains nearly all the peptides of PLA-7 precursor but has no peptides distinct from this latter. Similarly, OS1 is a competitor protein of PLA-1 precursor / OS5 precursor. Interestingly, secreted phospholipases A2 ($sPLA_2$s) and related proteins were highly represented in the identified proteins and constituted good candidates. We focused on two proteins having the highest number of identified peptides, *i.e.* OS1 and OS2 $sPLA_2$s (Table 1) and tested their activities on sperm mobility by using native and recombinant enzymes. A 10 min incubation with OS1 and OS2 at 200 nM modified the head sperm tracks recorded by the CASA system (Fig. 2A). The two sperm motility parameters VCL and ALH were decreased by both $sPLA_2$s (Fig. 2B-C), with OS2 being more potent than OS1. Interestingly, concentrations of OS2 as low as 0.2 nM were able to modify sperm VCL.

3.2. $sPLA_2$ catalytic activity is required for venom $sPLA_2$ effects on sperm motility

Snake venom $sPLA_2$s are structurally-conserved small enzymes with a low molecular mass of 13-18 kDa and are rich in disulfide bonds [17-19]. Snake venom $sPLA_2$s are divided into catalytically active and catalytically inactive enzymes. $sPLA_2$s bearing aspartate at position 49 (D49-$sPLA_2$s) are highly catalytically active whereas K49, S49- or N49-$sPLA_2$s present a low or no catalytic activity [20]. If $sPLA_2$ enzymes are first characterized by their ability to hydrolyze the *sn*-2 ester bond of glycerophospholipids to produce fatty acids and

lysophospholipids [21], they also act as agonists for specific lectin receptors and other proteins [22, 23]. Concerning neurotoxic $sPLA_2$, their mechanism of action is still an open question: some reports highlight the role of $sPLA_2$ metabolites, that are fatty acids and lysophospholipids [24] whereas others involve binding to proteins [13, 22]. Because several lectins receptors are present in the sperm membrane [25], we wondered which mechanism of action is involved in the effect of $sPLA_2$ on sperm motility. To investigate this question, we tested a H48Q catalytic mutant of OS2 which has a 500-fold lower catalytic activity than the wild-type enzyme [13, 26]. The H48Q OS2 mutant was inactive on sperm VCL (Fig. 3A). We also tested a chimeric OS2/OS1 $sPLA_2$ where the OS2 C-terminal domain (AA 109-128) has been substituted by the C-terminal domain of OS1. This OS2/OS1 chimera has a 500-fold lower enzymatic activity but interestingly retains most of the neurotoxicity of wild-type OS2 [13]. The chimera was also unable to inhibit sperm motility.

The above screening experiments have shown that venoms from *Echis carinatus*, *Bothrops alternatus* and *Macrovipera lebetina* were inactive. The two first venoms are characterized by the presence of a high level of $sPLA_2$ myotoxins [16, 27, 28], characterized by a mutation at amino acid 49 and leading to a strong decrease of its catalytic activity. We tested the purified $sPLA_2$-like myotoxins BaII-K49 and BaIV-K49 from the venom of *Bothrops asper* and found that both proteins were fully inactive on sperm motility (Fig. 3B). In good accordance, we found that a D49K mutant of OS2, which has no detectable enzymatic [13], was also inactive on sperm motility (Fig. 3B). All together, these results indicate the importance of the catalytic activity of OS1 and OS2 in decreasing sperm motility.

3.3. OS2 treatment does not impair sperm viability, but converts the fast-speed sperm population into the low-speed sperm population

Venoms are known to produce tissue lysis and cell death. We thus addressed whether the effect of OS2 on sperm motility was due to sperm lysis and death. We first measured the speed distribution of sperm treated with OS2 versus control (Fig. 4A). The distribution of OS2-treated sperm was characterized by the absence of fast sperm, i.e. sperm with a VCL above 200 µm/s, and by an over-representation of the slow sperm subpopulation, i.e. sperm with a VCL between 50-100 µm/s. On the other hand, OS2 treatment did not increase the immotile subpopulation (0-10 µm/s). The fact that most of the treated cells were still motile after treatment suggests that OS2 did not induce a fast cell death responsible for the measured effect on sperm motility, but rather converted the fast-speed sperm into low-speed ones. To confirm this result, we loaded OS2-treated sperm with 6-carboxyfluorescein diacetate (6-CFDA), a compound which is used as a marker of sperm viability and enters freely into living cells to produce green fluorescence after de-esterification by endogenous esterases [29]. OS2-treated sperm subsequently incubated with 6-CFDA presented a strong green fluorescence (Fig. 4B), indicating that OS2 treatment did not induce cell death. Finally, we measured phosphatidylserine staining with annexin-Cy3 before and after OS2 treatment, as a marker of changes in lipid asymmetry at the plasma membrane during $sPLA_2$ treatment. It is important to point out that in sperm cells, externalization of phosphatidylserine occurs naturally during capacitation and is not considered as a hint of apoptosis [30]. Interestingly, a 10 min treatment of non-capacitated sperm with OS2 induced a strong externalization of phosphatidylserine at the plasma membrane (Fig. 4C). All together, these results suggest that OS2 treatment produces a lipid reorganization of the plasma membrane similar to that occurring during capacitation and without inducing any obvious sperm cell death.

3.4. OS1 and OS2 are very potent modulators of acrosome reaction and fertilization

Different studies have shown that mammalian PLA_2s play important roles in capacitation, acrosome reaction (AR) and the early steps of fertilization including sperm binding and sperm-oocyte fusion [31]. AR induced by non physiological and physiological stimuli (Ca^{2+} ionophore, progesterone and zona pellucida) is prevented by PLA_2 inhibitors [32-35] and produce the release of lipid metabolites like fatty acids and lysophosphatidylcholine (LPC). Moreover, LPC and fatty acids accelerate or promote exocytosis [36, 37]. Finally, LPC improves sperm binding on zona pellucida [38] and sperm-oocyte fusion [39]. This physiological context prompted us to test the effects of OS1 and OS2 on AR and fertilization.

We thus tested the potency of OS1 and OS2 to induce AR. Dose-response curves showed that OS2 is more potent than OS1 to induce AR (Fig. 5). Importantly, only a fraction of the sperm subpopulation was sensitive to the $sPLA_2$. Indeed, concentrations above 100 nM did not further produce AR of the treated sperm, and about 40% of the sperm population appear to be resistant to OS2 treatment. This result may be explained by the presence of two sperm populations with a different sensitivity to OS2 and fits with earlier findings indicating that the sperm plasma membrane composition is heterogeneous [40].

We have shown that OS1 and OS2 are potent modulators of sperm physiology, inhibiting sperm motility, triggering sperm AR and producing lipid reorganization of the plasma membrane. We next evaluated the impact of such modifications on the sperm fertilization potential. To address this question, we compared *in vitro* fertilization outcomes obtained with control and OS2-treated sperm. We thus treated capacitated sperm briefly with 20 or 200 nM OS2 during 10 min before mixing sperm and oocytes for fertilization (Fig. 6A). Twenty four hours after fertilization, the rate of oocytes reaching the 2-cell embryo stage was counted and compared to IVF performed with untreated sperm and oocytes from the same batches (Fig. 6B). OS2 decreased the IVF outcomes in a dose-dependent manner (Fig. 6C). It is important to note that the fertilization rate is not modified for OS2-treated sperm. On the other hand,

embryos obtained with OS2-treated sperm presented a defect in the first step of development, corresponding to the first cleavage, as illustrated by the increased rate of aborted embryos.

4. Discussion

In this manuscript, we have shown that fractions from various snake venoms containing molecules below 15 kDa can inhibit sperm motility. Moreover, we found that the inhibiting activity from the venom of *Oxyuranus scutellatus scutellatus* on sperm motility is mostly due to compounds with a molecular mass around 10-15 kDa. By using a proteomic approach and purified toxins, we found that the effects of the active fraction were mostly due to the $sPLA_2$ OS1 and OS2. Indeed, recombinant OS1 and OS2 $sPLA_2$s inhibited sperm motility. Moreover, OS1 and OS2 activities on sperm motility were due to their enzymatic activity on phospholipids, since several types of enzymatically inactive mutants were unable to modulate sperm motility. Moreover, several snake venoms and more particularly those from *Echis carinatus*, *Bothrops alternatus* and *Macrovipera lebetina* were unable to modulate sperm motility. These venoms are rich in $sPLA_2$ myotoxins, which are characterized by a D49K mutation, leading to complete loss of enzymatic activity. In agreement, two purified $sPLA_2$-like myotoxins, BaII-K49 and BaIV-K49 that originate from the venom of *Bothrops asper*, were fully inactive on sperm motility. All together, these results demonstrate that the potency of a snake venom to decrease sperm motility is dependent on the catalytic activity of the $sPLA_2$s present in the venom. However, possible other inhibiting or activating effects of non-$sPLA_2$ compounds present in the venom may be masked by our screening procedure using pooled fractions and the strong inhibitory effects of $sPLA_2$ on sperm motility. Compounds with activating effects appeared to be present as suggested by the activating effect of fraction B1 of *Oxyuranus scutellatus s*.

The different secreted PLA_2s have been classified into ten different groups, namely I, II, III, V, IX, X, XI, XII, XIII and XIV $sPLA_2$ [41]. A large variety of $sPLA_2$ are found in venom of different animals such as insect (*Hymenoptera*), scorpions and snakes. Toxic $sPLA_2$ belong to three different groups: $sPLA_2$ from *Elapidae* and *Hydrophidae* snakes belong to

group IA, $sPLA_2$ from *Crotalidae* and *Viperidae* snakes belong to group IIA while $sPLA_2$ from *Hymenoptera* belong to group III. We did not observe a strong relationship between sperm activity and $sPLA_2$ group classification since both OS2 (group IA) and OS1 (group IB ; OS1 does belong to group IB since a typical pancreatic loop is present [42]) from *Oxyuranus scutellatus* and likely $sPLA_2$ from *Daboia russelli* (group IIA) were all active. The molecular diversity of snake venom $sPLA_2$ is particularly high and a single snake venom can contain up to 15 different $sPLA_2$, with different patterns of enzymatic activities and toxicities [17]. As also suggested by the different potencies of the snake venoms screened in this study, we observed that two different $sPLA_2$s from *Oxyuranus scutellatus scutellatus*, OS1 and OS2, presented marked differences in their ability to inhibit sperm motility, OS2 being about 10-fold more potent than OS1. Recently, a toxin complex called "reprotoxin" and containing an $sPLA_2$ subunit was found to induce atrophy of testis when injected at a sub-lethal dose [43]. Our results show that sperm membrane composition are deeply affected by $sPLA_2$ activity and may eventually lead to cell apoptosis. Our results may thus explain the testis atrophy induced by reprotoxin.

This study further confirms that changing the sperm plasma membrane composition, and more particularly phospholipids via $sPLA_2$ enzymatic activity, has important physiological consequences in terms of sperm motility, capacitation and acrosome reaction. It is important to point out that the strong decrease of sperm motility was not due to a loss of cell viability since OS2-treated sperm was still able to hydrolyze the fluorescent probe by non-specific esterases. The decrease of sperm motility was likely due to changes in the composition of the plasma membrane, as demonstrated by the change in annexin-V staining after OS2 treatment. This hypothesis is also supported by the fact that human astenozoospermia (sperm with low motility) is associated with a defective sperm plasma membrane composition with an excess of cholesterol and desmosterol [44, 45], a low concentration of specific fatty acids like

docosahexaenoic acid found in different phospholipids [46] and an overall increase of fatty acid content [47, 48]. These results suggest that lipid rearrangement or lipid metabolites are important for flagellum beat, in order either to change membrane fluidity or to control key proteins involved in flagellum beat. Venom $sPLA_2$s, by changing lipids of the plasma membrane, are likely to mimic the action of endogenous mammalian $sPLA_2$s, known to control sperm motility. For instance gene knock-out of the intracellular PLA_2 VIA ($iPLA_2\beta$) leads to a severe motility phenotype [49]. Overall, our results highlight the importance of $sPLA_2$ as a modulator of sperm physiology. Indeed, mammalian $sPLA_2$s are widely expressed in male reproductive tissues [50] and are likely to be involved in a large set of biological functions that remain to be determined.

OS1 and OS2 were also potent inducers of acrosome reaction, with marked effects at concentrations as low as 0.2 nM for OS2. Interestingly, the potent OS2 $sPLA_2$ was unable to trigger AR in the whole sperm population even at very high concentrations, and about 30-40% of sperm were fully resistant. This point highlights the heterogeneity of the sperm population [40, 47]. Finally, the fact that embryos obtained with OS2-treated sperm presented an impaired development during the first cleavage stresses the importance of the quality of the sperm plasma membrane composition and integrity for embryo development [51]. This result points out to the importance of sperm phospholipids in the first steps of embryo development.

In conclusion, our results highlight two important characteristics of mammalian sperm phospholipids during fertilization that include their heterogeneity and their role in embryo development. This point suggests that the lipid composition of the sperm should be taken into account in assisted reproductive techniques like ICSI (Intra Cytoplasmic Sperm Injection), where the physiological sperm sorting mechanisms, which are normally occurring in the female tract, are not reproduced [52].

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Table/Figures legends

Table 1: list of identified proteins in the fraction 9 of *Oxyuranus scutellatus*. N: rank of the specified protein relative to all other proteins in the list of detected proteins. Unused (ProtScore): measure of the protein confidence for a detected protein, calculated from the peptide confidence for peptides from spectra that have not been completely "used" by higher scoring winning proteins. Total (ProtScore): measure of the total amount of evidence for a detected protein. The Total ProtScore is calculated using all the peptides detected for the protein. % Cov (% Coverage): number of amino acids matching to at least one identified peptide divided by the total number of amino acids in the protein sequence, expressed as a percentage.

Fig. 1: Snake venoms modulate sperm motility. (A) Venoms were separated by size exclusion chromatography on a Superdex^{TM} peptide 10/300 GL. Fractions containing molecules above 15 kDa (A1-A8) were discarded and not tested. Example of separation for the crude venom of *Oxyuranus scutellatus scutellatus* (blue curve). A calibration run using cytochrome C (12.3 kDa), aprotinin (6.5 kDa) and vitamin B12 (1.8 kDa) is presented (red curve). (B) Global activity test of 16 different venoms on sperm motility. Aliquotes of fractions A9-B4 were pooled and tested as a single pooled fraction for their global activity on sperm VCL. (C) Effect of the different fractions (A9-B3) of *Oxyuranus scutellatus scutellatus* on sperm motility.

Fig. 2: OS1 and OS2, two sPLA$_2$s from the venom of *Oxyuranus scutellatus scutellatus* inhibit sperm motility. (A) Tracks of the head position of non capacitated sperm measured by the CASA system in three conditions: control (non treated) sperm, sperm treated with OS1

sPLA$_2$ and sperm treated with OS2 sPLA$_2$. (B) Dose-response curves corresponding to the inhibition of VCL by OS1 and OS2. (C) Similar dose-response curves for ALH.

Fig. 3: Inhibition of sperm motility by OS2 is dependent on its enzymatic activity.

(A) Comparison of the effects of OS1, OS2, OS2-H48Q (catalytically inactive mutant) and OS2-Cter (catalytically inactive OS2-OS1 chimera) on sperm motility at 200 nM. (B) Comparison of the effects of two different myotoxins (BaII-K49 and BaIV-K49 from the venom of *Bothrops asper*) and OS2-D49K (a catalytically inactive mutant) on sperm motility.

Fig. 4: OS2 is a potent activator of acrosome reaction. (A) Non capacitated control sperm: most sperm are non-acrosome reacted and exhibit dark staining in the apical head (arrows). (B) Sperm incubated for 10 min in the presence of 200 nM OS2: most sperm are acrosome reacted, as indicated by the absence of a stained region in the apical head (black arrows). Note that some sperm are non-acrosome reacted (white arrows) (C) Dose-response curves corresponding to the acrosome reaction triggered by OS1 and OS2. Spontaneous AR measured on untreated sperm was subtracted and the presented values correspond to sPLA$_2$-induced AR.

Fig. 5: OS2 does not induce a fast sperm death and triggers externalization of phosphatidylserine. (A,B) Distribution of the different subpopulations of sperm as a function of VCL or ALH values of non-treated control sperm (green bars), OS1-treated sperm (red bars) and OS2-treated sperm (black bars). (C,D) Non-capacitated sperm incubated in the presence of carboxyfluorescein diacetate (6-CFDA) for 15 min, after a 10 min pre-incubation with control medium (C) or 200 nM OS2 (D). (E,F) Non-capacitated sperm incubated in the

presence of annexin-V-cyanin-3 for 15 min, after a 10 min pre-incubation with control medium (E) or 200 nM OS2 (F).

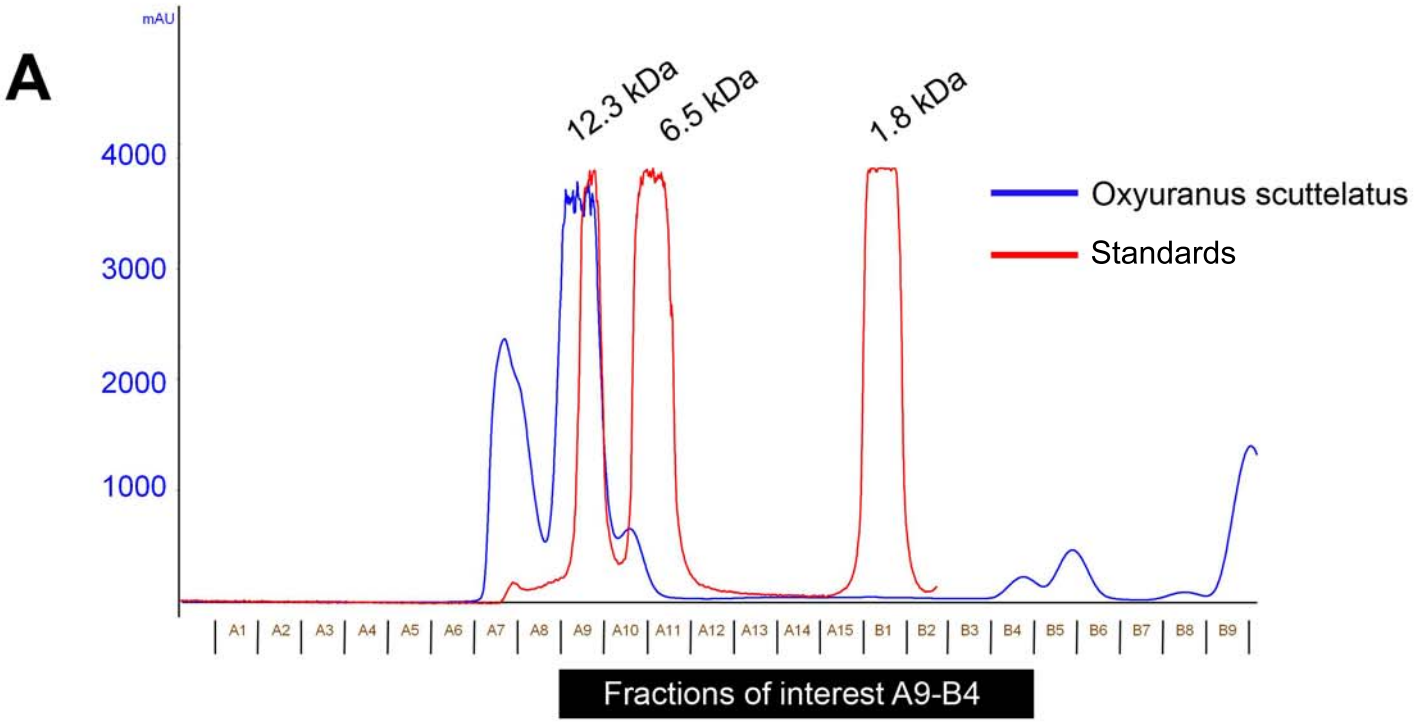
Fig. 6: Impaired *in vitro* development of embryos obtained with OS2-treated sperm. (A) Schematic drawing of a typical IVF experiment. Sperm were first capacitated for 35 min in M16-2% BSA and then incubated for the last 10 min with M16 medium containing 20 nM or 200 nM OS2. After treatment, sperm were washed by centrifugation to remove unbound OS2, putative catalytic products and all acrosomal compounds released during $sPLA_2$-induced AR. Finally, washed sperm were introduced into droplets containing oocytes (20-85 oocytes per experiment). After 4 h of gamete mixing, unbound sperm were washed away and IVF outcomes were scored at 24 h. (B) Pictures of the different stages obtained after IVF at 24 h: unfertilized oocytes; 2-cell embryos (normal development); aborted embryos corresponding to oocytes with either multiple and uncontrolled divisions or presenting a second polar body (PB) but no cell division. C. Outcomes of *in vitro* fertilization performed with either control sperm or sperm briefly treated with 20 or 200 nM OS2.

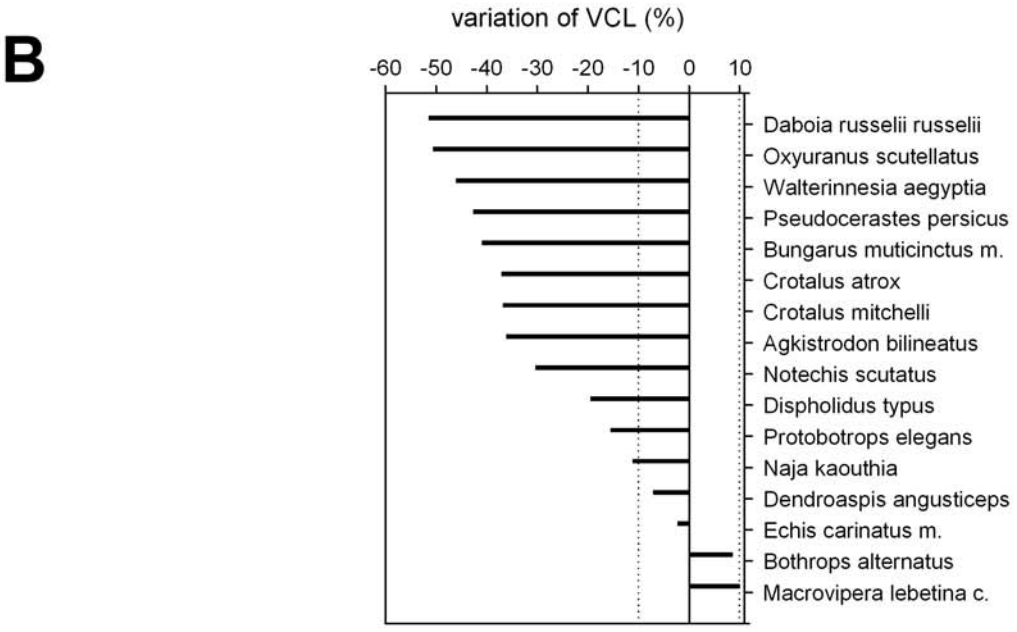
Tables

N	Unused	Total	%Cov	Accession	Name	Species
1	28,40	28,40	70,55	gi|71066730	PLA-7 precursor [Oxyuranus scutellatus]	Oxyuranus scutellatus
1	0,00	26,40	84,03	gi|913014	OS2=secretory phospholipase A2 [Oxyuranus scutellatus=Taipan snakes, ssp. scutellatus, venom, Peptide, 119 aa]	Oxyuranus scutellatus
2	16,54	16,54	64,94	gi|71066720	PLA-1 precursor [Oxyuranus scutellatus]	Oxyuranus scutellatus
2	0,00	16,54	64,94	gi|66475088	OS5 precursor [Oxyuranus scutellatus scutellatus]	Oxyuranus scutellatus scutellatus
2	0,00	16,00	73,23	gi|913013	OS1=secretory phospholipase A2 [Oxyuranus scutellatus=Taipan snakes, ssp. scutellatus, venom, Peptide, 127 aa]	Oxyuranus scutellatus
3	13,57	13,57	65,06	gi|71066802	SNTX-1 precusor [Oxyuranus scutellatus]	Oxyuranus scutellatus
3	0,00	13,57	65,06	gi|123910874	RecName: Full=Short neurotoxin 1; Short=SNTX-1; AltName: Full=Toxin 3; Flags: Precursor	Oxyuranus scutellatus scutellatus
3	0,00	13,52	57,83	gi|66475096	toxin 3 [Oxyuranus scutellatus scutellatus]	Oxyuranus scutellatus scutellatus
3	0,00	12,00	67,74	gi|254772678	RecName: Full=Short neurotoxin 2; Short=SNTX-2	Oxyuranus scutellatus scutellatus
4	10,69	10,69	91,94	gi|263546	taicatoxin serine protease inhibitor component [Oxyuranus scutellatus=Australian taipan snakes, ssp. scutellatus, venom, Peptide, 62 aa]	Oxyuranus scutellatus
5	10,00	14,00	57,93	gi|71066718	beta taipoxin variant 1 precursor [Oxyuranus scutellatus]	Oxyuranus scutellatus
5	0,00	14,00	57,93	gi|66475082	beta taipoxin precursor [Oxyuranus scutellatus scutellatus]	Oxyuranus scutellatus scutellatus
5	0,00	14,00	71,19	gi|129435	RecName: Full=Phospholipase A2 homolog, taipoxin beta chain	Oxyuranus scutellatus scutellatus
6	10,00	14,00	44,52	gi|66475084	alpha taipoxin-2 precursor [Oxyuranus scutellatus scutellatus]	Oxyuranus scutellatus scutellatus
7	8,01	8,01	40,22	gi|254772668	RecName: Full=Long neurotoxin 1; Short=LNTX-1; Flags: Precursor	Oxyuranus scutellatus scutellatus
7	0,00	8,01	40,22	gi|118151706	LNTX-1 precursor [Oxyuranus scutellatus]	Oxyuranus scutellatus
8	6,89	14,89	70,59	gi|129413	RecName: Full=Phospholipase A2, taipoxin alpha chain; AltName: Full=Phosphatidylcholine 2-acylhydrolase	Oxyuranus scutellatus scutellatus
9	6,00	26,00	69,86	gi|66475090	OS6 precursor [Oxyuranus scutellatus scutellatus]	Oxyuranus scutellatus scutellatus
9	0,00	24,00	68,49	gi|66475092	OS7 precursor [Oxyuranus scutellatus scutellatus]	Oxyuranus scutellatus scutellatus
10	6,00	10,00	56,82	gi|239977265	RecName: Full=Venom protease inhibitor 1; Flags: Precursor	Oxyuranus scutellatus scutellatus
10	0,00	10,00	56,82	gi|239938649	RecName: Full=Taicatoxin, serine protease inhibitor component; Short=TCX; Flags: Precursor	Oxyuranus scutellatus scutellatus
10	0,00	10,00	56,82	gi|185533608	taicatoxin serine protease inhibitor precursor [Oxyuranus scutellatus]	Oxyuranus scutellatus
10	0,00	10,00	56,82	gi|129919019	venom protease inhibitor precursor [Oxyuranus scutellatus]	Oxyuranus scutellatus
10	0,00	10,69	62,50	gi|239977272	RecName: Full=Venom protease inhibitor 2; Flags: Precursor	Oxyuranus scutellatus scutellatus
10	0,00	10,69	62,50	gi|129919043	venom protease inhibitor precursor [Oxyuranus scutellatus]	Oxyuranus scutellatus
11	4,96	4,96	75,00	gi|348613	alpha-neurotoxin-like taicatoxin component - Australian taipan (fragment)	Oxyuranus scutellatus scutellatus
11	0,00	4,96	75,00	gi|263548	taicatoxin alpha-neurotoxin-like component {N-terminal} [Oxyuranus scutellatus=Australian taipan snakes, ssp. scutellatus, venom, Peptide Partial, 28 aa]	Oxyuranus scutellatus
12	4,00	4,00	53,33	gi|71725729	venom natriuretic peptide OsNP-d precursor [Oxyuranus scutellatus]	Oxyuranus scutellatus
12	0,00	4,00	53,33	gi|123916490	RecName: Full=Natriuretic peptide OsNP-d; Flags: Precursor	Oxyuranus scutellatus scutellatus
12	0,00	4,00	29,73	gi|189047090	RecName: Full=Peptide TNP-b; AltName: Full=Taipan natriuretic peptide; AltName: Full=Venom natriuretic peptide OxsSNPb; Flags: Precursor	Oxyuranus scutellatus scutellatus
12	0,00	2,00	88,57	gi|32363244	RecName: Full=Peptide TNP-b; AltName: Full=Taipan natriuretic peptide; AltName: Full=Venom natriuretic peptide OxsSNPb	Oxyuranus scutellatus canni
12	0,00	2,00	88,57	gi|32363241	RecName: Full=Peptide TNP-a; AltName: Full=Taipan natriuretic peptide; AltName: Full=Venom natriuretic peptide OxsSNPa	Oxyuranus scutellatus canni
12	0,00	2,00	88,57	gi|32363240	RecName: Full=Peptide TNP-a; AltName: Full=Taipan natriuretic peptide; AltName: Full=Venom natriuretic peptide OxsSNPa	Oxyuranus scutellatus scutellatus
12	0,00	2,00	28,21	gi|32363246	RecName: Full=Peptide TNP-c; AltName: Full=Taipan natriuretic peptide; AltName: Full=Venom natriuretic peptide OxsSNPc	Oxyuranus scutellatus canni
13	4,00	4,00	37,35	gi|239977119	RecName: Full=Scutellin-3; Flags: Precursor	Oxyuranus scutellatus scutellatus
13	0,00	4,00	37,35	gi|185534290	scutellin-3 precursor [Oxyuranus scutellatus]	Oxyuranus scutellatus
13	0,00	4,00	37,35	gi|157683297	scutellin-3 precursor [Oxyuranus scutellatus]	Oxyuranus scutellatus
14	2,00	4,00	29,73	gi|66475094	natriuretic peptide [Oxyuranus scutellatus scutellatus]	Oxyuranus scutellatus scutellatus
14	0,00	4,00	29,73	gi|189047090	RecName: Full=Peptide TNP-b; AltName: Full=Taipan natriuretic peptide; AltName: Full=Venom natriuretic peptide OxsSNPb; Flags: Precursor	Oxyuranus scutellatus scutellatus
15	2,00	4,00	12,50	gi|66475086	gamma taipoxin-2 precursor [Oxyuranus scutellatus scutellatus]	Oxyuranus scutellatus scutellatus
15	0,00	4,00	14,29	gi|129446	RecName: Full=Phospholipase A2, taipoxin gamma chain; AltName: Full=Phosphatidylcholine 2-acylhydrolase	Oxyuranus scutellatus scutellatus
16	2,00	2,00	3,27	gi|145982762	scutellatease-1 [Oxyuranus scutellatus]	Oxyuranus scutellatus

Table 1, Escoffier et al.

Figure 1





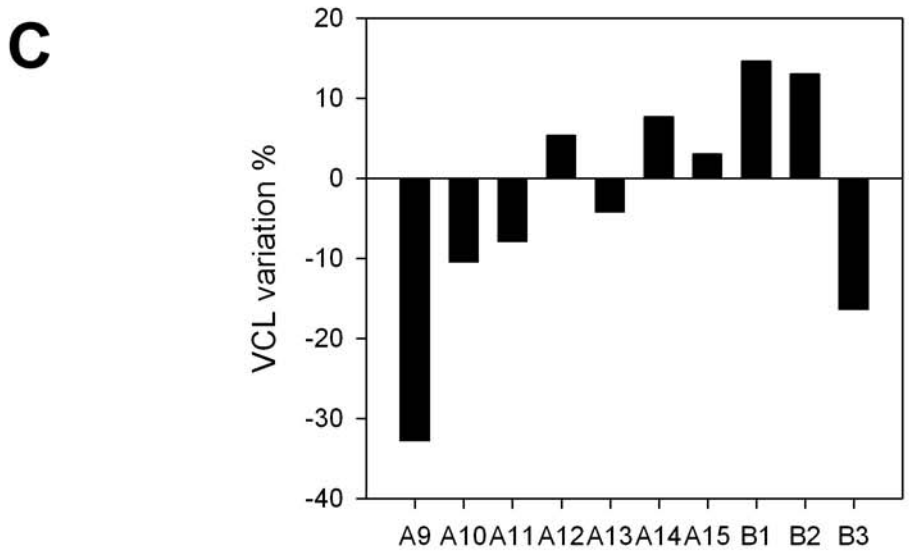


Figure 1, Escoffier et al

Figure 2

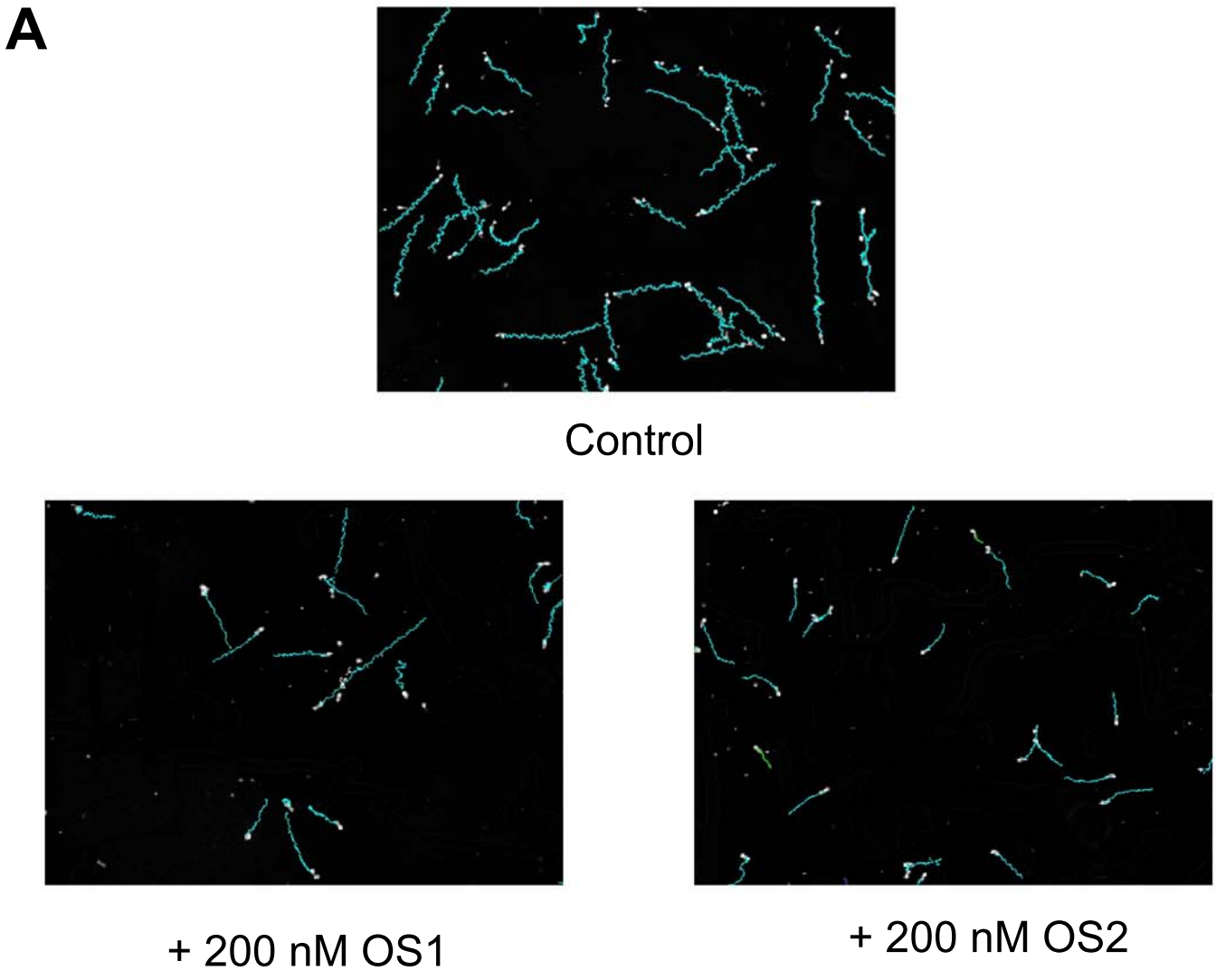


Figure 2, Escoffier et al.

Figure 3

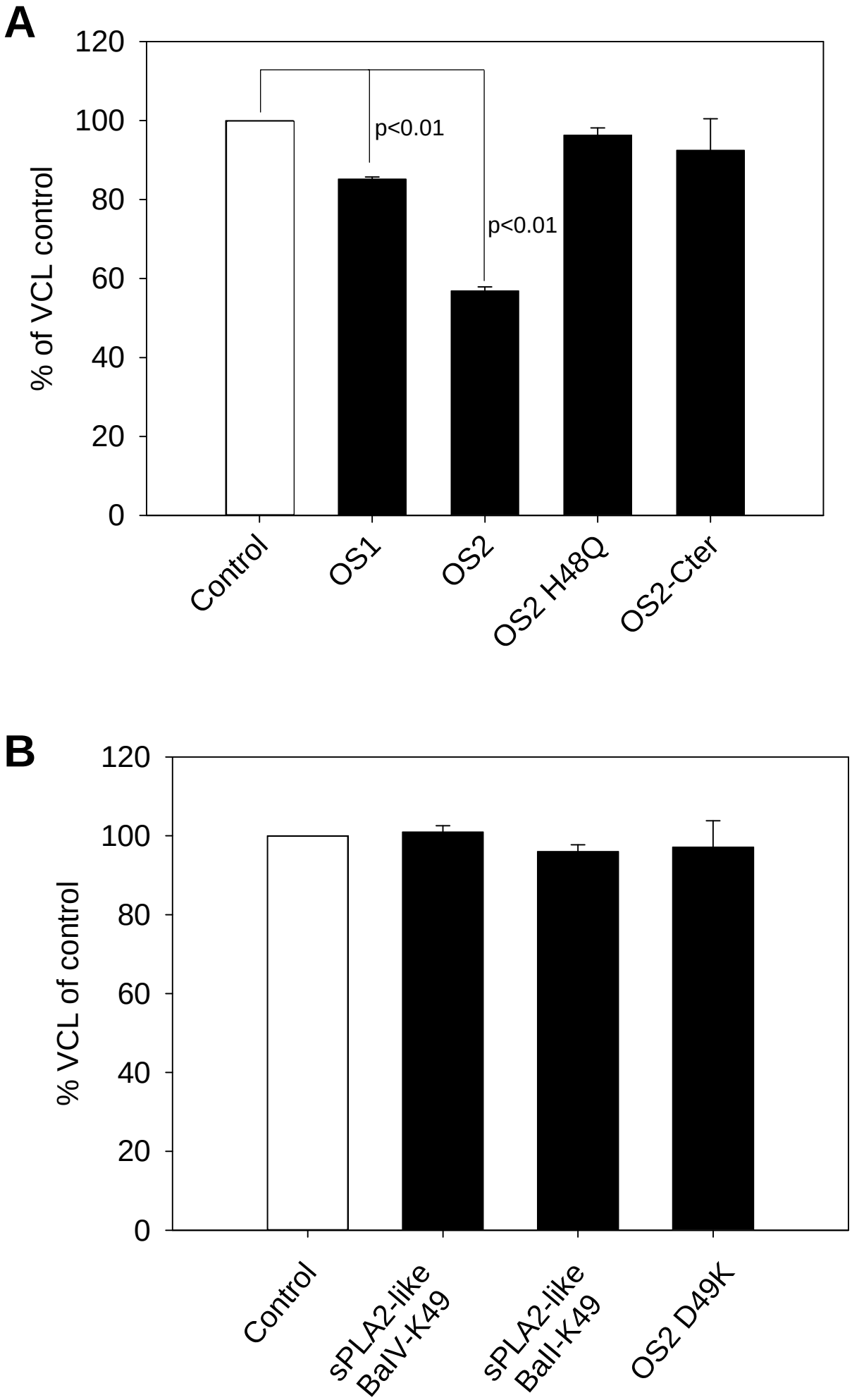


Figure 3. Escoffier et al.

Figure 4

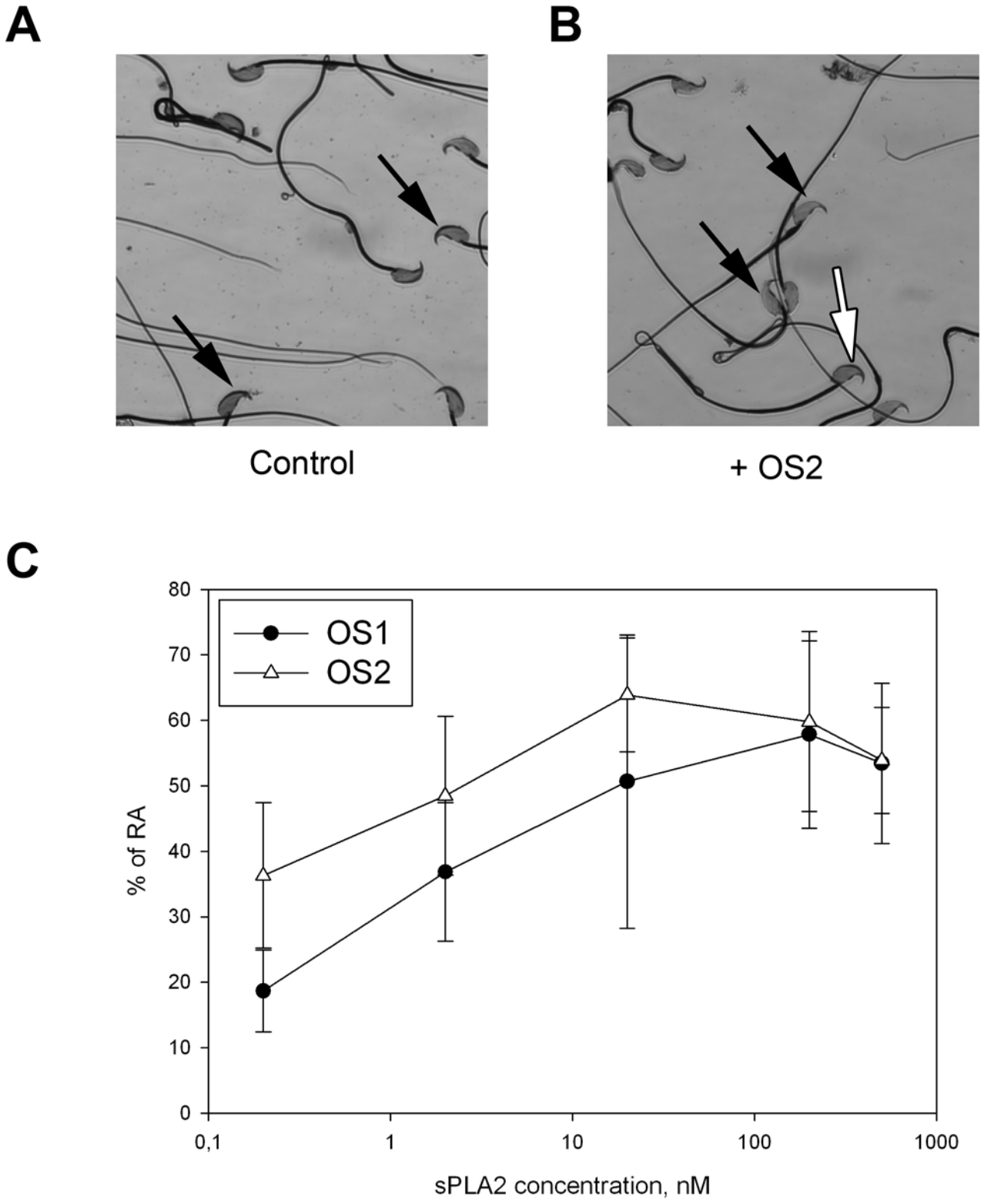


Figure 4, Escoffier et al.

Figure 5

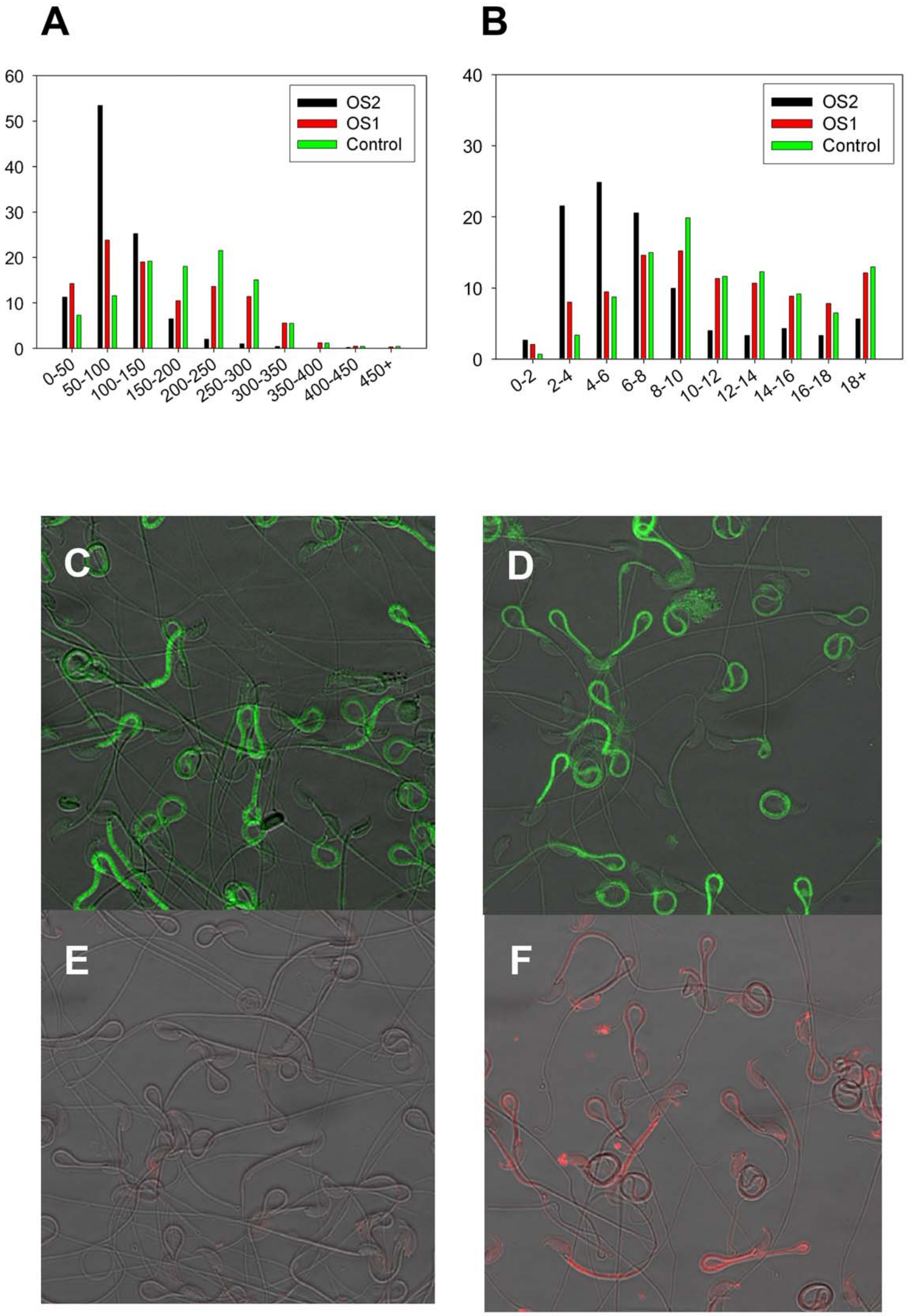
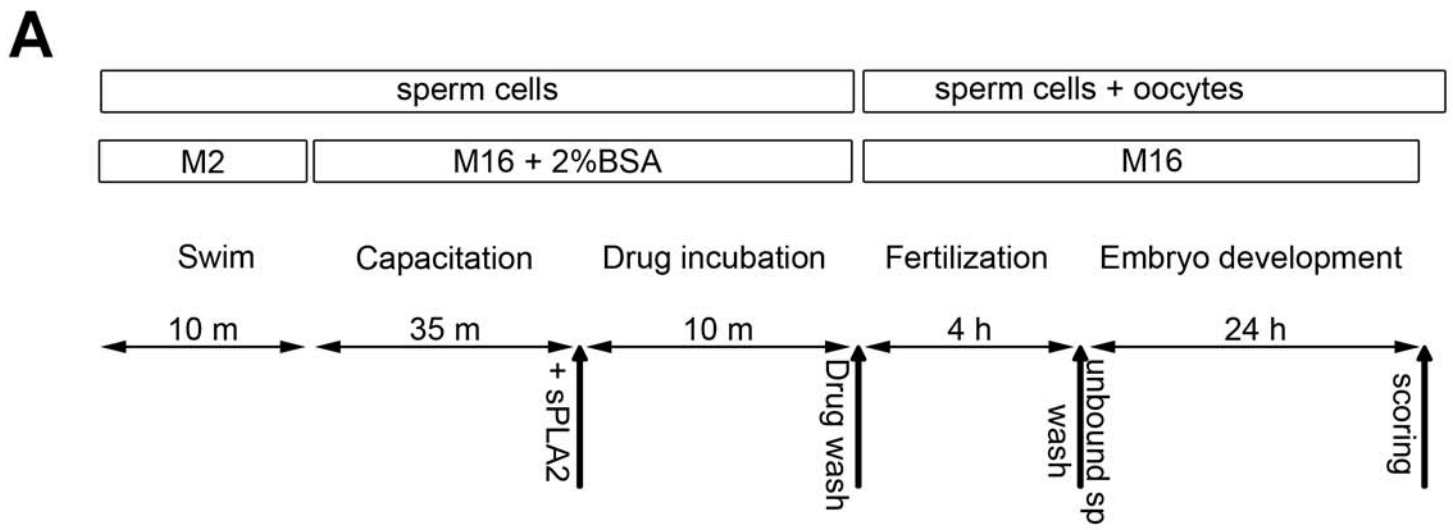
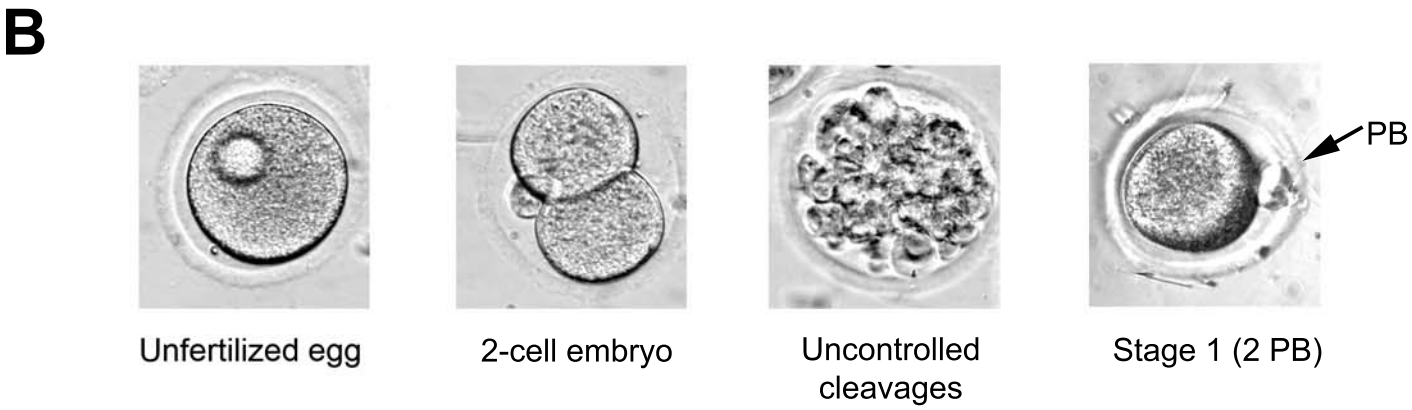


Figure 5, Escoffier et al.

Figure 6





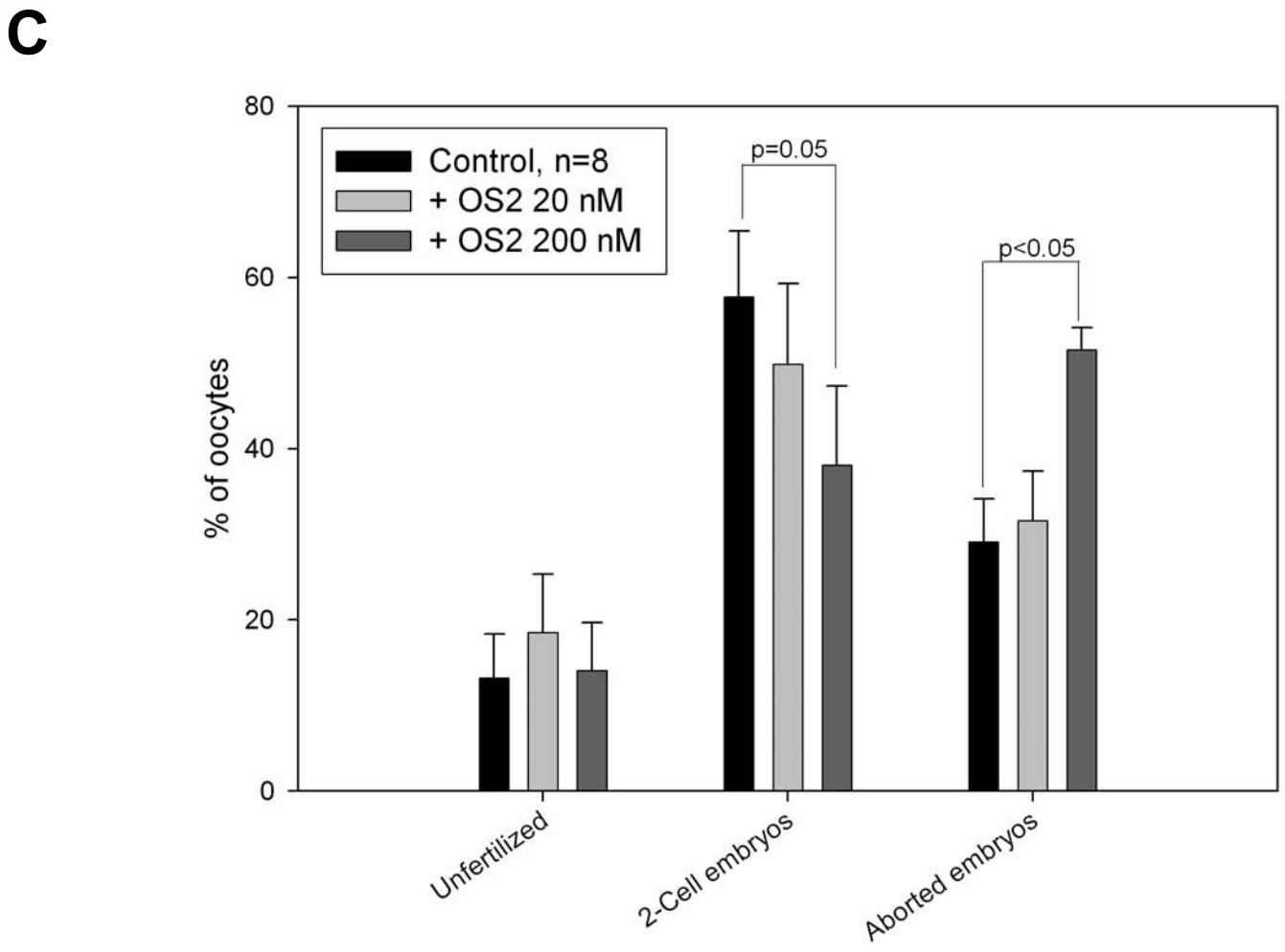


Figure 6, Escoffier et al.