



Oxidative damage in trout erythrocyte in response to “in vitro” copper exposure

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ABSTRACT

The oxidative action of copper on different trout *Oncorhynchus mykiss* erythrocyte components was studied. The results indicate that:

- cupric ions differently influence the oxidative status of two trout hemoglobin components I and IV (HbI and HbIV) having different structural and functional properties;
- reactive oxygen species (ROS) production associated with hemoglobins autoxidation is not influenced by the presence of copper sulfate;
- the susceptibility to hemolysis increases in the presence of copper only when the erythrocyte suspension is incubated in air; the effect of copper is almost absent for carbon monoxide-saturated erythrocyte suspensions;
- DNA damage due to copper was not observed in our experimental conditions.

The data obtained are important for the analysis of the environmental risks produced by copper on fish.

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1. Introduction

Copper is an essential trace metal for living organisms and its role as cofactor for crucial enzymes (cytochrome c oxidase, superoxide dismutase, ceruloplasmin, monooxygenases) has been well established. Most of these enzymes catalyze oxidation/reduction reactions that have molecular oxygen as co-substrate. However, if copper is present at relatively high concentrations in the environment, toxicity to aquatic organisms can occur (Winger et al., 2000; Marcano et al., 1996; Roche and Boge, 1996). In aquaculture systems, copper is regularly used in the form of copper sulfate as a therapeutic agent and it is widely used to control alga blooms and aquatic macrophyte infestations (Boyd and Massaut, 1999).

There is no doubt that exposure to excess copper can damage cells and organs because copper ion and its complexes can induce formation of reactive oxygen species that can damage biomolecules such as lipids, proteins and DNA. Copper toxicity at the cellular level depends on the permeability of cell membranes to copper ions and on its participation in redox reactions because it easily cycles between the cuprous and cupric state.



This paper focuses on the “in vitro” effects of copper ions on oxidative damage in trout *Oncorhynchus mykiss* erythrocytes. The effect of copper ions on the oxidation of trout hemoglobin components either as purified proteins or in the whole hemolysate was examined. It is worth recalling that contrary to mammals and birds, a multiplicity of hemoglobin components is generally present in erythrocytes of fish. In the case of nucleated erythrocytes from trout *O. mykiss*, four different hemoglobin components are present; they are characterized by functional differences which have been correlated with different physiological roles (Brunori, 1975). Trout hemoglobin components according to their anionic mobility have been called HbI, HbII, HbIII and HbIV. These hemoglobins are prone to oxidation and this property permits to follow “in vitro” the autoxidation process over a relatively short time. The production of reactive oxygen species during the hemoglobin oxidation was also evaluated. The measurements regarding purified hemoglobins were performed on HbI and HbIV. These two trout hemoglobin components represent, respectively, about 20% and 60% of the whole pigment present inside trout erythrocytes and have very different oxygen binding properties (Brunori, 1975). The mechanism of copper-induced met-hemoglobin formation has been described in detail for human hemoglobin solutions (Bonaventura et al., 1999) but this is not well understood for fish hemoglobins that have different structures. Furthermore, the influence of copper on the extent of hemolysis and on the susceptibility of DNA to oxidative damage was assessed.

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2. Materials and methods

All the reagents used were of analytical grade.

2.1. Samples

Red blood cells were obtained from *O. mykiss* trout, coming from the fish farm “Eredi Rossi Silvio” Sefro MC, Italy. The fish were kept in tanks containing water from Scarsito River, a tributary of the Potenza River, and fed with commercial fish food obtained from Hendrix S.p.A (Mozzecane, VR, Italy). Blood was extracted by puncturing the lateral tail vein. After washing with isotonic medium at pH 7.8 (0.1 M phosphate buffer 0.1 M NaCl, 0.2% citrate, 1 mM EDTA) the cells were suspended in the desired isotonic buffer.

2.2. Separation of hemoglobin components and carbon monoxide hemoglobin (HbCO) formation

Separation of the various hemoglobins, as described previously (Binotti et al., 1971) was carried out by column chromatography on DEAE-Sphadex A-50; their homogeneity was tested by electrophoresis.

Experiments involving carbon monoxide (CO) hemoglobin were carried out after exposure of the oxygenated derivative to a weak vacuum by using a rotary vane pump and then to pure CO gas. The vacuum, performed for a few seconds, permits the removal of part of the oxygen thus making the formation of CO hemoglobin easier (Hb affinity for CO is greater than that for O₂ by about 250-fold).

2.3. Ferric hemoglobin (Met-Hb) formation and hemoglobin precipitation

The rate of met-Hb formation in the hemolysates and in two electrophoretically distinct hemoglobin components called hemoglobin trout I and IV (HbI and HbIV) was followed in a Cary 219 spectrophotometer in the visible region; reference value (i.e. complete oxidation) was estimated by addition of ferricyanide. Absorbance at 700 nm was followed as an index of turbidity to monitor the onset of hemoglobin precipitation.

2.4. Reactive oxygen species production during Hb oxidation

ROS production associated with Hb autoxidation was evaluated by monitoring the oxidation of non-fluorescent dichlorofluorescein (DCFH) to fluorescent DCF.

A solution of 1 mg ml⁻¹ of HbI or HbIV was incubated for 1 h in phosphate buffer 50 mM pH 7.5 at different temperatures and in the presence of 0.036 μM DCFH and of 10 or 100 μM CuSO₄. DCFH oxidation was measured fluorimetrically on these solutions at excitation and emission wavelengths of 498 nm and 520 nm, respectively.

2.5. Hemolysis

In order to evaluate the hemolysis rate, the erythrocytes were suspended in isotonic medium at pH 6.3 at 35 °C. The degree of hemolysis was determined spectrophotometrically at 540 nm as previously described (Falcioni et al., 1987) either in the presence or absence of the desired amount of copper sulfate. In particular, hemolysis was determined as $100 \times A/10 \times A^* \times 100\%$ where *A* is the optical density of Hb present in the supernatant after centrifugation of red cell suspension and *A** × 100% is the optical density of

the red cell suspension after complete lysis with 10 volumes of distilled water at zero time incubation.

2.6. Single-cell gel electrophoresis (comet assay)

The “comet” assay was performed on trout erythrocytes (1×10^6 cells ml⁻¹) incubated in a pH 6, 3 isotonic buffer at 35 °C for 1 h in the presence and absence (control) of 50 μM copper sulfate. After incubation, the erythrocytes were suspended in 0.7% low melting agarose in phosphate buffer saline (PBS) and pipetted on microscope slides pre-coated with a layer of 1% normal melting agarose. The agarose with the cell suspension was allowed to set on the pre-coated slides at 4 °C for 10 min. Subsequently, another top layer of 0.7% low melting agarose was added and allowed to set at 4 °C for 10 min. The slides were then immersed in lysis solution (1% sodium *n*-lauroyl-sarcosinate, 2.5 M NaCl, 100 mM Na₂EDTA, 10 mM Tris HCl pH 10, 1% Triton X-100 and 10% dimethyl sulfoxide for 1 h at 4 °C in the dark, in order to lyse the embedded cells and to permit DNA unfolding. After incubation in lysis solution, slides were exposed to alkaline buffer (1 mM Na₂EDTA, 300 mM NaOH buffer, pH >13) for 20 min; in this condition RNA is completely degraded. The slides were subjected to 20 min electrophoresis at 25 V in the same alkaline buffer and finally washed with 0.4 M Tris HCl buffer (pH 7.5) to neutralize excess alkali and to remove detergents before staining with ethidium bromide (2 μg ml⁻¹).

Cells were examined with an Axioskop 2 plus microscope (Carl Zeiss, Germany) equipped with an excitation filter of 515–560 nm and a magnification of ×20. Imaging was performed using a specialized analysis system (“Metasystem” Altusheim, Germany) to determine tail moment (TM), tail length (TL) and tail intensity (TI), parameters correlated with the degree of DNA damage in each single cell. Experiments were performed three times and data (at least 150 scores per sample) are the mean values plus/minus the standard error of the mean (SEM). Statistical analysis was performed using the student *t*-test and differences were regarded as statistically significant when *p* values were <0.05.

3. Results

3.1. Met-Hb rate formation in hemolysates

Fig. 1 is one representative set of tracings from a total of at least three experiments and shows the time course of hemoglobin autoxidation during incubation at 35 °C in 50 mM phosphate buf-

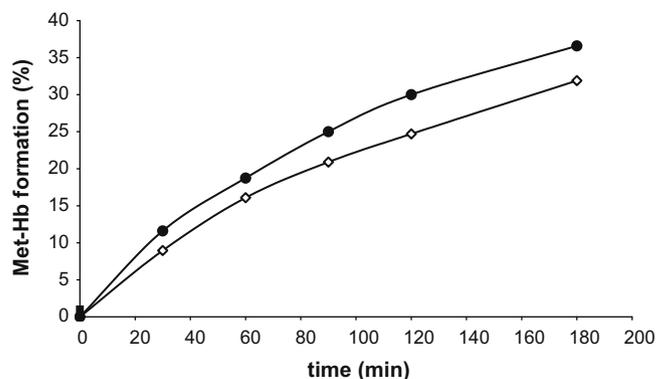


Fig. 1. Time course of Hb autoxidation in trout hemolysate containing Hb (1 mg ml⁻¹) during incubation at 35 °C in phosphate buffer 50 mM pH 7.5 in the presence and in the absence of 10 μM CuSO₄. Data are from one representative set of tracings from a total of three experiments. (◇) control and (●) +10 μM CuSO₄.

fer, pH 7.5, of trout hemolysate in the absence and presence of $10 \mu\text{M}$ CuSO_4 . As can be observed, the presence of $10 \mu\text{M}$ CuSO_4 increases the met-Hb formation rate; after 2 h of incubation, the level of met-Hb was $\sim 30\%$ and $\sim 25\%$ in the presence and absence of copper sulfate, respectively. The statistical analysis of the three experiments give a p value < 0.05 .

3.2. Met-Hb rate formation in purified hemoglobin components HbI and HbIV

Fig. 2 shows the time course of HbI autoxidation when the protein was incubated at 35°C and pH 7.5. The presence of high amounts of CuSO_4 (up to $100 \mu\text{M}$) does not influence the HbI oxidation rate with respect to the control (HbI alone without CuSO_4) during our incubation time.

It was not possible to perform similar experiments with HbIV because this hemoglobin component is less stable and tends to precipitate under these experimental conditions. The presence of copper sulfate accelerates the protein denaturation rate. A similar behaviour was also observed at lower incubation temperatures (30°C).

3.3. Reactive oxygen species production during Hbs incubation

ROS production associated with Hb autoxidation was followed by means of fluorescence deriving from DCFH oxidation. Figs. 3 and 4 show the time course of DCF fluorescence generated during 1 h incubation of HbI or HbIV followed at different temperatures. After 1 h of HbI incubation at 20°C and 25°C there is no ROS formation and this is in agreement with the absence of HbI oxidation. When the HbI solution is incubated for 1 h at 35°C ROS formation due to the partial oxidation of the protein was observed (Fig. 3). Similar experiments were performed with HbIV (the highest temperature was 30°C) (Fig. 4). A slight ROS production was present also at 25°C which increased at 30°C . For both hemoglobins the level of ROS production was not influenced by the presence of copper sulfate. It is possible to avoid the formation of met-Hb by adding carbon-monoxide (CO) before incubation. Experiments performed with HbCO did not show ROS formation at any temperature (data not shown). This behaviour is due to the stability versus the oxidation of the carbomonoxy-derivative; in other words, HbCO does not lead to the ferric form during incubation.

3.4. Hemolysis rate

By varying pH and temperature, it is possible for trout erythrocytes suspended in isotonic medium to follow “in vitro” the hemo-

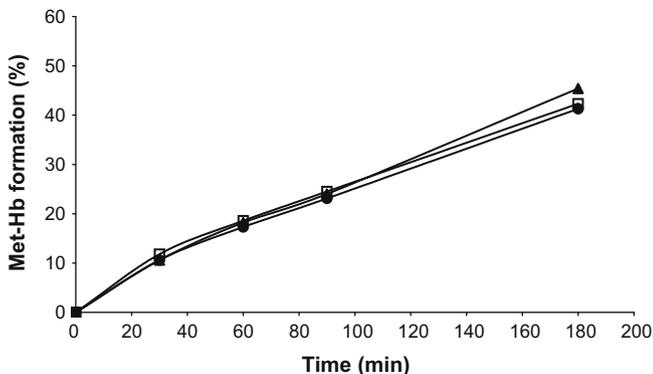


Fig. 2. Time course of 1 mg ml^{-1} HbI autoxidation during incubation at 35°C in phosphate buffer 50 mM pH 7.5 in the presence and in the absence of 10 and $100 \mu\text{M}$ CuSO_4 . Data are from one representative set of tracings from a total of three experiments. (●) control; (□) $+10 \mu\text{M}$ CuSO_4 and (▲) $+100 \mu\text{M}$ CuSO_4 .

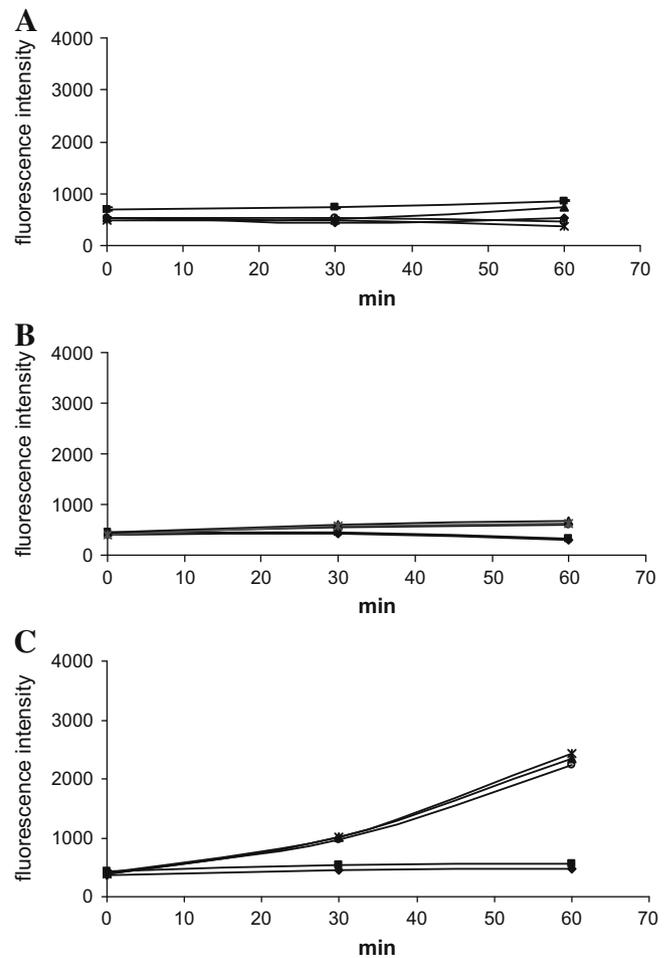


Fig. 3. Time course of DCFH ($0.036 \mu\text{M}$) fluorescence generated during 1 h incubation of HbI (1 mg ml^{-1}) in phosphate buffer 50 mM pH 7.5 at 20°C (Panel A), at 25°C (Panel B) and at 35°C (Panel C) in the presence and absence of 10 and $100 \mu\text{M}$ CuSO_4 . Data are from one representative set of tracings from a total of three experiments. (●) Phosphate buffer + DCFH; (■) phosphate buffer + $100 \mu\text{M}$ CuSO_4 + DCFH; (▲) phosphate buffer + HbI + DCFH; (○) phosphate buffer + HbI + $10 \mu\text{M}$ CuSO_4 + DCFH and (*) phosphate buffer + HbI + $100 \mu\text{M}$ CuSO_4 + DCFH.

lytic event over a relatively short time (Falcioni et al., 1987); the hemolytic process is characterized by the presence of a long lag phase. The influence of a fixed amount ($50 \mu\text{M}$) of copper sulfate on the rate of hemolysis in trout erythrocytes during incubation in isotonic buffer at 35°C and pH 6.3 was investigated and reported in Fig. 5. The figure is one representative set of tracings from a total of at least three experiments. The susceptibility to hemolysis increases in the presence of copper only when the erythrocyte suspension was incubated in air; a dose-dependent effect of copper was absent for CO-saturated erythrocyte suspensions exposed to air under identical conditions. The half time ($t/2$) of hemolysis (expressed as the time necessary for 50% hemolysis to occur) and determined from Fig. 5 is 160 min, 186 min, 148 min and 183 min for red blood cells (RBC) suspension in air, RBC suspension with CO, RBC suspension in air with $50 \mu\text{M}$ CuSO_4 and RBC suspension with CO and $50 \mu\text{M}$ CuSO_4 , respectively. The statistical analysis of the three experiments give a p value < 0.05 .

3.5. Comet assay

The “comet assay” or single-cell gel electrophoresis was performed on trout erythrocyte suspension to explore if the copper salt under study influenced the DNA status in these nucleated cells.

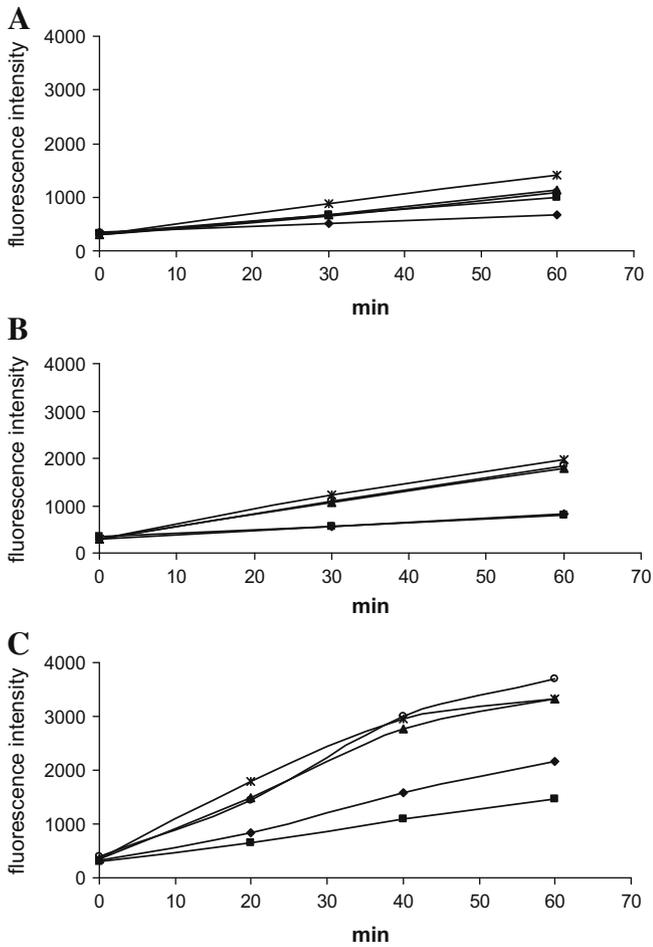


Fig. 4. Time course of DCFH (0.036 μM) fluorescence generated during 1 h incubation of HblV (1 mg ml^{-1}) in phosphate buffer 50 mM pH 7.5 at 20 °C (Panel A), at 25 °C (Panel B) and at 30 °C (Panel C) in the presence and absence of 10 and 100 μM CuSO_4 . Data are from one representative set of tracings from a total of three experiments. (◆) Phosphate buffer + DCFH; (■) phosphate buffer + 100 μM CuSO_4 + DCFH; (▲) phosphate buffer + HblV + DCFH; (○) phosphate buffer + HblV + 10 μM CuSO_4 + DCFH and (*) phosphate buffer + HblV + 100 μM CuSO_4 + DCFH.

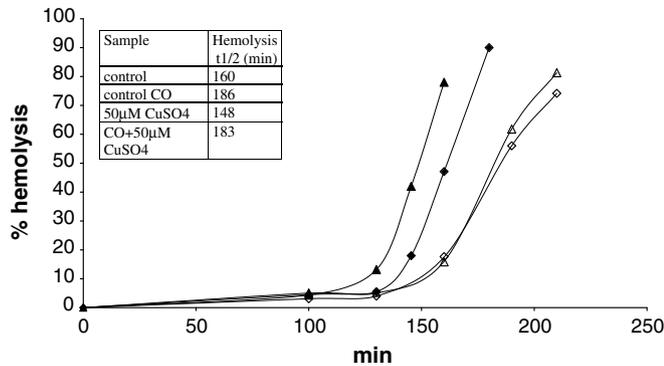


Fig. 5. Time course of hemolysis of trout erythrocyte suspensions ($\text{Hb} = 30 \text{ mg ml}^{-1}$) incubated in isotonic buffer pH 6.3 and at 35 °C in presence and absence of carbon monoxide and 50 μM CuSO_4 . Data are from one representative set of tracings from a total of three experiments. (◆) control; (▲) + 50 μM CuSO_4 ; (◇) control CO and (Δ) CO + 50 μM CuSO_4 .

This test has become increasingly popular for the measurement of DNA damage in individual cells and consists of embedding cells in agarose, followed by lysis, electrophoresis and staining to visualize DNA damage using fluorescence microscopy. Cells with increased DNA damage display an increased migration of genetic material in the direction of the electrophoresis. The extent of DNA damage is quantified by measuring the displacement of the genetic material between the cell nucleus (“comet head”) and the resulting “tail”. The parameters used as an index of DNA damage are tail length, tail intensity and tail moment and they are calculated by computerized image analysis. The “comet assay” was performed on trout erythrocyte suspensions incubated at pH 6.3 and 35 °C for 60 min in the presence of 50 μM copper sulfate. Fig. 6 clearly shows that all the considered comet parameters (tail length, tail intensity and tail moment) increased after 1 h. The increase for tail length and tail moment was independent of the presence of copper

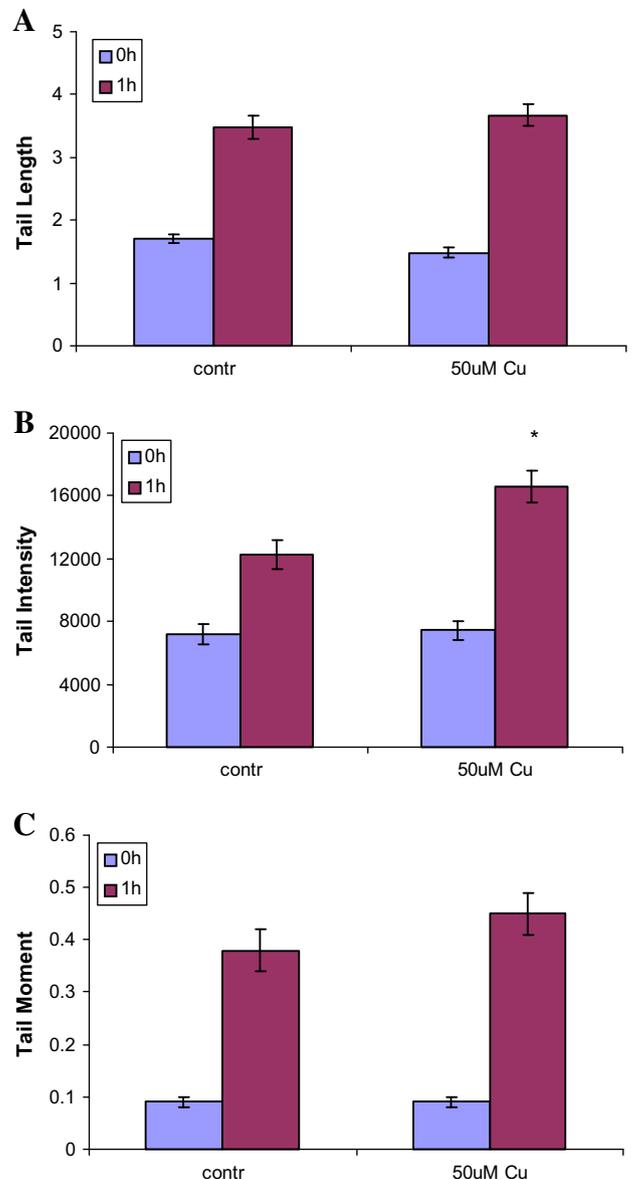


Fig. 6. Tail length (A), tail intensity (B) and tail moment (C) comet parameter (mean \pm s.e.m) measured on trout erythrocyte suspension incubated in isotonic buffer at pH 6.3 and at 35 °C for 1 h in the presence and in the absence of carbon monoxide and 50 μM CuSO_4 . * $p < 0.05$ compared to control 1 h.

sulfate in the incubation medium; a slight increase was instead measured for tail intensity.

4. Discussion

It is well known that copper can induce damage to cells through radical-formation (Valko et al., 2005; Gaetke and Chow, 2003). Furthermore it is important to remember that copper, together with iron and selenium, control the activity of those enzymes involved in the defence mechanisms against reactive oxygen species (superoxide dismutase, catalase and glutathione peroxidase). The results reported here clearly show that the presence of copper can influence the redox state of HbIV and disrupts the plasma membrane. However, under our experimental conditions DNA damage due to the presence of copper was not observed, except for a slight increase in tail intensity.

There is evidence that copper catalyzes human oxyhemoglobin oxidation also at very low concentrations (Rifkind, 1974; Wint-erborn and Carrel, 1997) while other metal ions have no significant effect even at high concentrations. The copper induced met-Hb formation mechanism has been described in detail for human hemoglobin (Bonaventura et al., 1999). It is probable that ferric hemoglobin formation, in general, involves an electron transfer from Fe^{2+} to Cu^{2+} as suggested for human hemoglobin (Bonaventura et al., 1999). Our results on the effect of copper on autoxidation of trout hemoglobins clearly show that the effect of the metal is different in the two hemoglobin fractions HbI and HbIV that have different aminoacid sequences, and as a consequence, different tridimensional structures and functional properties (Barra et al., 1983; Petruzzelli et al., 1989).

The involvement of the sulphhydryl group in β -93 position in hemoglobin autoxidation has been reported in the literature (Rifkind, 1972). The effect of copper on Hb oxidation during the hemolysate incubation reported in Fig. 1 could imply that the hemoglobin component oxidized is HbIV and not HbI. This is due to the fact that HbI in the presence of copper at the highest concentration and in the same experimental conditions was not oxidized.

It is worth pointing out that the autoxidation of oxygenated Hbs can be followed by the transformation of the oxidized molecule (high-spin Fe^{3+}) into a species absorbing as a low-spin Fe^{3+} compound, that is a hemichrome which tends to precipitate. The overall process may be described according to the following scheme:



The presence of different antioxidant enzymes (superoxide dismutase, catalase and glutathione peroxidase) in the hemolysate could reduce the oxidation rate of HbIV and thus avoiding the formation of HbIV precipitate.

The conversion of oxyhemoglobin into met-Hb is associated with superoxide production (Misra and Fridovich, 1972; Brunori et al., 1975) and thereby of products such as H_2O_2 or hydroxyl radical, which can derive from O_2^- itself.

We have observed that the presence of copper sulfate does not influence the level of ROS during 1 h of HbI or HbIV incubation (Figs. 3 and 4). This result could be due to the direct interaction between heme-iron and copper or to the participation of copper in redox reactions involving ROS.

The presence of Cu^{2+} in the trout erythrocyte suspension influences the hemolytic process (Fig. 5) when the cells are exposed to air. The effect of Cu^{2+} is absent when the experiment was performed with CO-saturated erythrocytes; the presence of CO leads to insignificant hemoglobin auto-oxidation over the same time range. These data appear to indicate that the effect of Cu^{2+} on lysis is also correlated with hemoglobin oxidation. The hemolytic event

is a complex process due to more than one type of biochemical damage. The difference in the rate of hemolysis between red blood cells saturated with either CO or O_2 was due to the consequences following hemoglobin oxidation (Falcioni et al., 1987). Recently, Labieniec et al. (2009) found that incubation with copper of marine fish erythrocytes from *Dicentrarchus labrax* increased hemolysis of cells; a significant decrease in the hemoglobin content and red blood cells after exposure of fish *Channa punctatus* to sublethal concentration of copper sulfate has been reported by Singh et al. (2008). On the membrane surface as well as at the cytosol level, copper ions are involved in various redox reactions that lead to an increased radical production followed by oxidative damage and lipid bilayer destruction. Cupric but not cuprous ions are responsible for met-Hb formation that can contribute to the hemolytic event. The reduction of cupric to cuprous ion can occur at the membrane surface level (Bogdanova et al., 1999) by the involvement of sulphhydryl groups. Both cupric and cuprous ions can interact with transport systems outside and inside the membrane leading to its perturbation (Bogdanova et al., 2002).

5. Conclusions

In conclusion, the environmental risks from the use of copper compounds should be evaluated in order to control biological damage to fish. The results here presented indicated that an eventual “in vivo” alteration following copper exposure could induce plasma membrane perturbation with a mechanism involving methemoglobin formation.

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