An Acad Bras Cienc (2021) 93(2): e20191450 DOI 10.1590/0001-3765202120191450
Anais da Academia Brasileira de Ciências | *Annals of the Brazilian Academy of Sciences*
Printed ISSN 0001-3765 I Online ISSN 1678-2690
www.scielo.br/aabc | www.fb.com/aabcjournal

CELLULAR AND MOLECULAR BIOLOGY

Effect of taurine associated gold nanoparticles on oxidative stress in muscle of mice exposed to overuse model

ANAND THIRUPATHI, HELEN R. SORATO, PAULO R.L. SILVA, ADRIANI P. DAMIANI, VANESSA M. ANDRADE, PAULO C.L. SILVEIRA, RENATA T. NESI, MARCOS M.S. PAULA & RICARDO A. PINHO

Abstract: Muscle overuse and its consequent muscle damage has no cure. Therefore, the present study aimed to investigate the regulatory role of tau-AuNPs on muscle recovery of muscle overuse model. The animals (Male Swiss mice) were randomly divided into four groups: Control (Ctr; n=6); tau-AuNPs (n=6); overuse (n=6); and overuse plus tau-AuNPs (n=6). Exercise sessions were performed for 21 consecutive days, and one exercise model was applied daily in the following sequence: low intensity, moderate intensity, and high intensity. The mice were then sacrificed. The quadriceps muscles were surgically removed for subsequent biochemical analysis (oxidative stress parameters, DNA damage markers and muscle differentiation protein). The overuse group significantly increased the oxidative stress parameters and DNA damage markers, whereas tau-AuNPs significantly decreased the oxidative stress parameters in the overuse animal model. However, there were no significant differences observed between overuse group and overuse plus tau-AuNPs administrated group in relation to DNA damage markers including DNA damage frequency and index levels when compared to control and tau-AuNPs groups. Muscle differentiation protein Myf-5 was increased in the overuse plus tau-AuNPs administration group when compared to control group. In conclusion, tau-AuNPs had significant effect on reducing oxidative stress parameters and increasing myogenic regulatory protein Myf-5 in the overuse group. However, it did not have significant effect on reducing DNA damage.

Key words: Muscle overuse, taurine, AuNPs, oxidative stress.

INTRODUCTION

The repetitive microtrauma in relation to volume and intensity of the physical exercise can fail the muscle adaptation potentiality is named overuse caused injury. This has a serious consequence in terms of negatively promoting number of cellular and biochemical alterations in the muscular system (DiFiori et al. 2014). In general, muscle adaptation needs sufficient recovery time, but in case of overuse muscles do not get enough recovery time, leads reactive oxygen species production (ROS) and further ROS induced damages in the cellular and subcellular components of muscles (Thirupathi et al. 2018). Since ROS carry out some of the major signaling for muscle improvements including adaptation and plasticity, it is important to maintain the redox balance (Brown & Griendling 2015, Powers et al. 2011).

Number of exogenous antioxidants have been used to balance the muscle redox system (Ostjen et al. 2018, Silva et al. 2010, Sakellariou et al. 2016). In a recent work, our group have shown

that taurine (tau) supplementation modulates various cellular remodeling parameters after overuse-induced muscle damage, and these positive effects may be related to its antioxidant capacity (Thirupathi et al. 2018). Tau is a thiol based amino acid synthesized through cysteine metabolism; and can also be obtained exogenously. Although it does not participate in the structure of proteins and enzymes, tau has an important regulatory function in calcium fluxes, DNA protection (Thirupathi et al. 2018), in the stabilization of cell membrane structure (Schaffer et al. 2010), and in the regulation of inflammatory mediators (da Silva et al. 2014, Nakajima et al. 2010). In addition, the tau supplementation has a positive effect on redox homeostasis in the skeletal muscle (McLeay et al. 2017, et al. 2017, Seidel et al. 2018). However, the accuracy of tau`s antioxidant property in the cellular level is inconclusive and limited.

Due to versatile characteristics of gold nanoparticles (AuNPs), it can be used for a wide range of biomedical applications. The binding potential between the analytes and the AuNPs can facilitate the physiochemical properties of AuNPs which has a profound effect on biological situation. Previous study has reported that thiol association with AuNPs improved the redox system (Paula et al. 2015). This association might be exerting antioxidant and anti-inflammatory action for improving the redox system (Victor et al. 2012) and the AuNPs also have high reactive centres, which can bind strongly to thiol groups of intracellular compounds (Levy et al. 2004). In addition, AuNPs can penetrate into cells and carry biologically active substances (Jin et al. 2010, Arvizo et al. 2010). Since tau and AuNPs possessing cellular regulatory properties and biological functions, it is believed that the association of both molecules can decrease the oxidative stress, and further consequent DNA damage, and increase the degree of cellular protection for facilitating the process of muscle repair, particularly in muscle injury conditions.

MATERIALS AND METHODS

Preparation of Tau-AuNPs

Tau synthetic 99% was acquired from Sigma-Aldrich (T0625). AuNPs were prepared by reduction of tetrachloroauric acid (Sigma-Aldrich - St. Louis, MO, USA) with sodium citrate (Nuclear Diadema, SP, Brazil) and characterized as previously described (Paula et al. 2015). Briefly, 35 uL of HAuCl 4 was diluted in 100 mL of water and the solution was harmed until 90 °C under magnetic stirring. Then, 5 mL of sodium citrate (10 mmol/L) was added, and the system maintained under reflux and stirring at 700 rpm for 20 min. The interaction between AuNPs and tau was evaluated by UV-vis spectroscopy via surface plasmon resonance (SPR) band using a Shimadzu instrument model UV-1800 (Shimadzu Corp., Kyoto, Japan). Briefly, 0.1 mL of tau at 0.10 mol / L, 0.25 mol / L, and 0.50 mol / L aliquots were added to 1 mL of AuNPs solution and the UV-vis spectra registered. Tau-AuNPs FTIR spectra were recorded employing a Fourier transform infrared Shimadzu IRAffinity-1S. In this case, a solution of tau-AuNPs was deposited on the surface of the sample holder, and then it was kept in a desiccator under reduced pressure until complete evaporation of the water.

Animals

Male Swiss mice (30–35 g) were obtained from our own breeding colony. The animals were housed according to the experimental design to a cage, on a 12 h light/dark cycle (lights on at 07:00), with free access to food (Nuvilab CR1, Nuvital Nutrientes S/A, Brazil) and water. All experimental procedures were performed in accordance with the Brazilian Guidelines for the Care and Use of Animals for Scientific

and Didactic purposes (DOU 27/5/13, MCTI, p.7), and the local ethics committee approved the study. The animals were randomly divided into four groups: Control (Ctr; n=6); tau-AuNPs (n=6); overuse (n=6) and overuse plus tau-AuNPs (n=6).

Overuse model

All the animals were habituated on a nine-channel, motor-driven treadmill at a speed of 10 m min−1 for 10 min/day for one week to reduce the stress of a new environment. The mice did not receive any stimuli to run. The overuse model consisted of three different exercise types: low intensity (60 minutes at a speed of 13 m.min-1, no incline), moderate intensity (60 minutes at a speed of 17 m. min1, no incline), and high intensity (inclination -16% until exhaustion at a speed of 17 m.min-1- eccentric exercise). The exhaustion was considered by the inability of the animals to maintain a continuous rhythm (remained for 30 seconds or more at the bottom of lane run). Exercise sessions were performed for 21 consecutive days, and one exercise model was applied daily in the following sequence: low intensity, moderate intensity, and high intensity.

Tau-AuNPs administration

100 µL of Tau-AuNPs were administered subcutaneously on the back of the animals immediately after the high-intensity exercise.

Sample preparation

Twenty-four hours after the last exercise session, twenty microliters of blood were collected from the tail of the animal to determine the DNA damage. After this proceeding, the animals were killed by decapitation and the right quadriceps (central portion) were surgically removed and immediately processed or aliquoted and stored at -70°C for subsequent biochemical analysis. The central portion (50mg) of left quadriceps was immediately homogenized in specific buffer containing 1% Triton X-100, 100 mMTris (pH 7.4), 100 mM sodium pyrophosphate, 100 mM sodium fluoride, 10mM ethylenediaminetetraacetic acid (EDTA), 10mM sodium vanadate, 2mM phenylmethylsulfonyl fluoride (PMSF), and 0.1 mg/ml aprotinin at 4°C with Polytron MR 2100 (Kinematica, Switzerland). The homogenate was centrifuged at 11,000 rpm for 30 minutes at 4°C. The concentration of total proteins was determined from the supernatant (Bradford 1976). The proteins were resuspended and stored in Laemmli buffer containing 100 mmol/L dithiothreitol (DTT) for further immunoblotting assay with specific antibodies.

Oxidative stress parameters

Oxidized intracellular 2',7'-dichlorofluorescein (DCF) levels were monitored in samples incubated with 2',7'-dichlorodihydrofluorescein (DCFH). The formation of the oxidized fluorescent derivative was monitored at excitation and emission wavelengths of 488 and 525 nm, respectively, using a fluorescence spectrophotometer instruments. The malondialdehyde (MDA) concentrations in the tissue samples were determined by reverse phase high performance liquid chromatography (Prominence, Shimadzu Corporation, Japan), using a column Ascentis® C18 - 250 x 2.1 mm, 5 µm (Supelco, Sigma-Aldrich) using a thiobarbituric acid derivatization (Grotto et al. 2007). A standard curve was prepared using malondialdehyde tetrabutylammonium salt at concentrations ranging from 0.5 to 5.0µM. Total thiol content (sulfhydryl) was determined using DTNB oxidation as a reference. The reaction was initiated by adding 30 µl of 10 mM DTNB to phosphate-buffered saline. Following 30 min of incubation at room temperature, the absorbance at 412 nm was measured and the amount of TNB formed was calculated (equivalent to the thiol group content), as previously described (Ellman 1959).

Comet assay

Comet assays were performed under alkaline conditions (Tice et al. 2000) and visual scores were classified (Collins et al. 1997). The blood sample was placed in cold PBS and minced with a syringe plunger to obtain a fine cell suspension. Aliquots (20 µL) were embedded in low melting agarose (0.75%, w/v; 80 µL). These mixtures were then deposited onto microscope slides, which were precoated with normal melting point agarose (1.5%, w/v) and furnished with coverslips (two slides per sample). The slides were briefly placed on ice and the cover slip was carefully removed. The base slides were immersed in freshly prepared lysis solution (2.5 M NaCl, 100 mM EDTA, and 10 mMTris, pH = 10.0–10.5), before being immersed for 20 min in freshly prepared alkaline buffer (290 mMNaOH, 1 mM EDTA, pH > 13). Next, electrophoresis experiments (15 min/290 mA; 25 V; 0.7 V/cm) were performed using the same buffer. All these steps were carried out in the minimal indirect light. Following electrophoresis, the slides were neutralized with 400 mMTris (pH = 7.5) and stained with ethidium bromide solution (10 mg/mL). Damage indexes (DI) were calculated by visually separating the cells into five classes according to their tail size (0 = no tails to 4 = maximum-length tails). An individual DI was thus obtained for each sample and subsequently for each group studied. The group DIs ranged between 0 (completely undamaged = 100 cells × 0) and 400 (maximum damage = 100 cells × 4). The damage frequency (DF in %) was calculated for each sample, based on the number of cells with tails compared to those without. Visual scores for a Comet assay are a reliable evaluation method and usually agree closely with computer-based image analysis methods. All slides were coded for blind analysis.

Protein content

Protein levels were measured in all samples using the Bradford method (Bradford 1976) which is based on an absorbance (595 nm) shift of the dye Coomassie brilliant blue G-250 in which the red form of the dye is converted into its bluer form upon binding to the protein in the sample. Protein standards were obtained by diluting a stock solution of bovine serum albumin. Linear regression was used to determine the actual protein concentration of each sample.

Western Blot

250 µg of protein per sample were applied on polyacrylamide gel (SDS-PAGE). Electrophoresis was performed in a Mini-PROTEAN® Tetra electrophoresis system (Bio-Rad, Hercules, CA, USA), with electrophoresis buffer solution. Proteins separated on SDS-PAGE were transferred to the nitrocellulose membrane using the Mini Trans-Blot® Electrophoretic Transfer Cell (Bio-Rad) equipment. Nitrocellulose membranes containing the transferred proteins were incubated in blocking solution for 2 hours at room temperature to decrease non-specific protein binding. Membranes were then incubated with specific primary antibodies, anti-Myf-5 acquired from Cell Signaling Biotechnology (Beverly, MA, USA) under constant and overnight stirring at 4°C. Original membranes were reblotted with β-actin as the control protein and then incubated in solution with peroxidase conjugated secondary antibody for 2 hours at room temperature. Then, membranes were incubated for 2 minutes with enzymatic substrate and exposed to the RX film in a developing cassette. Intensity and area of the bands were captured using a scanner (HP G2710), quantified through the Scion Image program (Scion Corporation, Frederick, MD, USA).

Statistical analysis

All data are presented as mean ± SEM and differences between groups were analyzed using one-way analysis of variance (ANOVA) followed by Tukey post-hoc tests. $P<0.05$ was considered statistically significant. All statistical analyses were performed using the Graph Pad Prism 7 software.

RESULTS

Tau-AuNPs interaction

The electronic spectra of AuNPs and tau-AuNPs are presented in figure 1a and show a surface plasmon resonant (SPR) band with maximum absorption at 525 nm, typical of spherical gold nanoparticles. As can be seen, the addition of tau at different concentrations did not affect the SPR band. The UV-vis spectra of the AuNPs remained unchanged even after 12 h of addition of tau, regardless of the concentration of tau, indicating the stability of the solutions. Warming solutions also showed no effect. Finally, it was not possible to synthesize AuNPs replacing sodium citrate and using tau as a reducing and stabilizing agent. The figure1b shows the vibrational spectra of tau and tau-AuNPs obtained by FT-IR (Fourier transform infrared spectroscopy) in the ATR mode and shows that all vibrational modes of tau are preserved after association with AuNPs.

Oxidative stress indicators

Both DCFH oxidation (Figure 2a) and MDA level (Figure 2b) were significantly increased in the overuse group when compared to control, whereas combined Tau-AuNPs decreased the ROS generation and lipid peroxidation in the overuse group. Sulfhydryl content was decreased in the overuse group when compared to control group, but the administration of Tau-AuNPs did not significantly reverse these alterations in skeletal muscle (Figure 2c).

DNA damage indicators

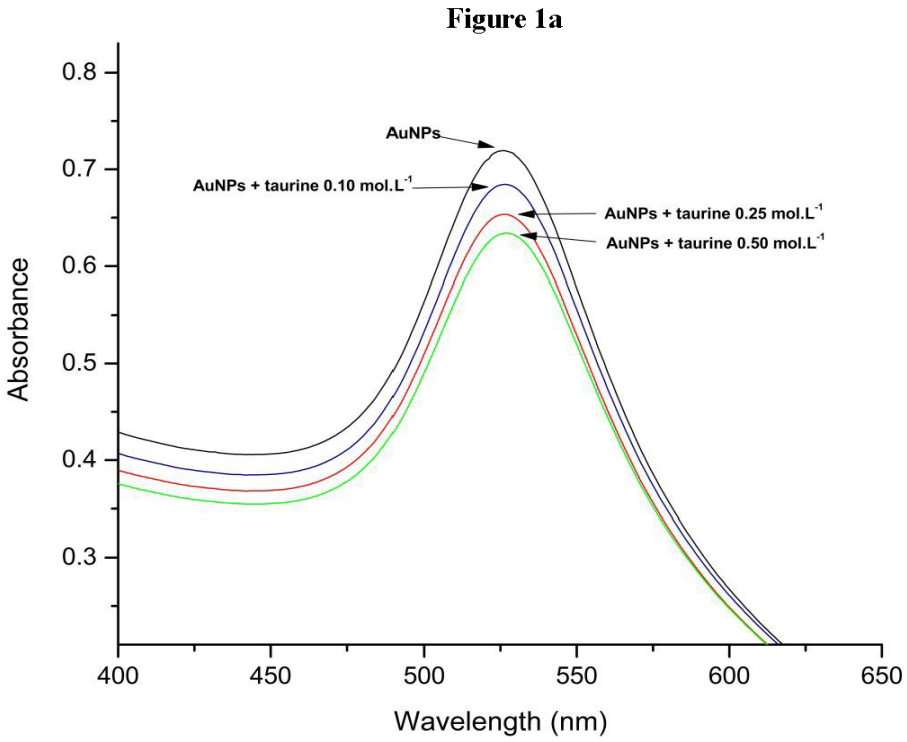
The frequency and index of DNA damage in blood were used as genotoxicity parameters. As we expected, the overuse group had high level of DNA frequency (Figure 3a) and index (Figure 3b), but there were no significant differences observed in both parameters of Tau-AuNPs administration group when compared to overuse group.

Muscle differentiation protein

Muscle differentiation proteins are important markers for finding muscle damage and repairing. We analysed the myf-5 protein is an important muscle differentiation protein. The level of muscle differentiation protein myf-5 was significantly decreased in the overuse group; whereas the administration of Tau-AuNPs increased the myf-5 level significantly when compared to control and overuse groups (Figure 4).

DISCUSSION

The interactions of thiol-AuNPs at the cellular level can modulate several biological processes such as inflammation, oxidative stress, tissue repair, and has now become the focus of several research groups. Tau or 2-aminoethanesulfonic acid, is an amino acid of molecular formula $C2H7NO3S$ which contains the functional groups -NH2 and -SO3H. The metal atoms in the surface of gold nanoparticles can interact with donor-acceptor species or ligands in a similar way as the related metal complexes (Grove & Karpowicz 2017, Toma et al. 2010). Previously, we reported the interaction between AuNPs and NAC (N-acetylcysteine), and its further biological



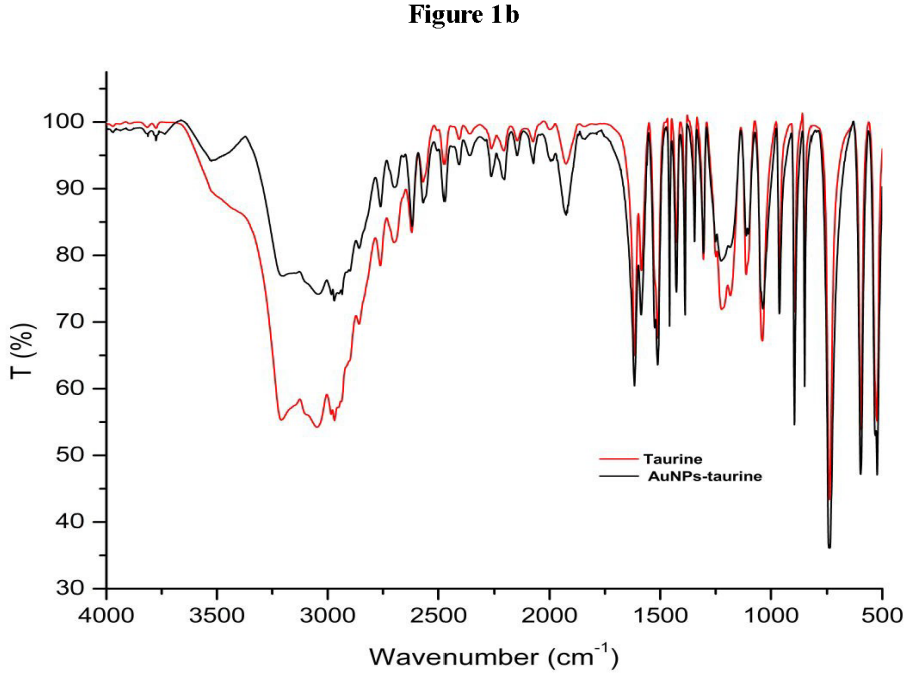


Figure 1. Represents the surface plasmon resonant (SPR) (a) band with maximum absorption at 525 nm. Addition of different concentration tau did not influence the SPR band. Vibrational spectra of tau and tau-AuNPs obtained by FT-IR in the ATR mode (b).

effects. NAC present a -SH group, while tau present a -SO 3H group, which explains the difference in the UV-vis spectrum of the NAC-AuNPs when compared to those of the tau-AuNPs. Here, we analysed the tau associated gold nanoparticle in reducing oxidative stress, and DNA damage induced by muscle overuse. Our results revealed an important role of the association of these molecules in mechanisms that regulate the recovery process after muscle

Figure 2a

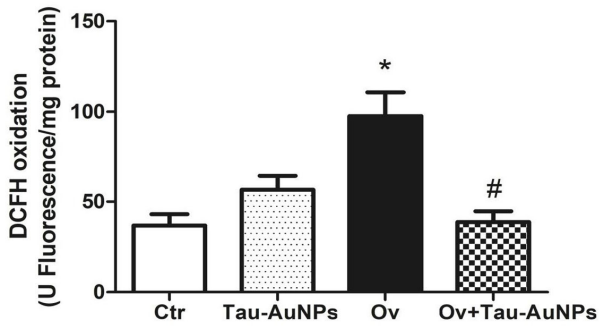


Figure 2b

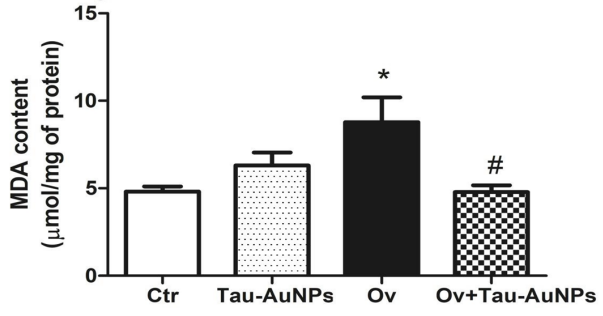


Figure 2c

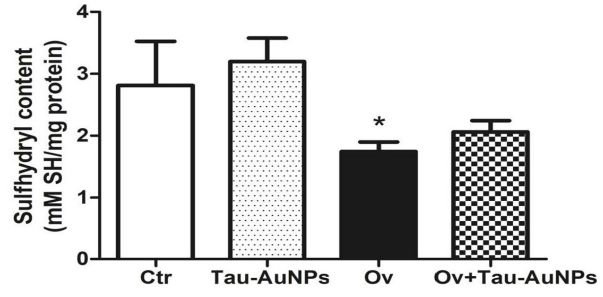


Figure 2. DCFH oxidation (a) and oxidative damage in the lipids (b) and thiol groups (c) of the quadriceps muscles of mice submitted to muscle overuse and tau-AuNPs administration. The results are expressed as the mean and SEM and were analyzed by one-way ANOVA followed by the post-hoc Bonferroni test. *p≤0.05 compared to the control; #p≤0.05 compared to the overuse group. All statistical analyses were performed using Graph Pad Prism 7 software. Groups: control (Ctrl), tau-AuNPs, overuse (Ov), overuse plus tau-AuNPs (Ov+Tau-AuNPS).

injury. Although the interaction between tau-AuNPs, based on the UV-vis and FTIR spectra, is not so evident, it is noticeable that the concomitant administration of tau-AuNPs have a biological effect, and capable of altering several biochemical parameters, as shown by the results of this study. In addition, the maintenance of the vibrational modes in the FTIR spectrum corroborates the UV-vis results, and in agreement with reported previously by Grove and Karpowicz (Grove & Karpowicz 2017).

Muscular systems are the primary site for metabolic insults and adaptation. Regular exercise with optimum level has beneficial effects on muscles, but unaccustomed exercise with higher intensity has deleterious effect on muscles including ROS production and consequent muscle damage. Several studies have observed that tau scavenge the ROS and regulate the antioxidant defense mechanism (Jong et al. 2012, Zhang et al. 2014). However, its role in the cellular level as antioxidants is still debatable. Therefore, we attempted to use first time for the association of tau-AuNPs as ROS scavenger to counteract the ROS during muscle overuse. As we expected, overuse animal with tau-AuNPs decreased the ROS production. The possible way for scavenge the overuse induced ROS by tau-AuNPs is diverse the electrons from electron transport chain to oxygen molecule, and AuNPs can facilitate the entrance of tau into mitochondria (Daniel & Astruc 2004). Our previous study found that tau regulates the mitochondrial complexes in order to reduce the ROS production in the overuse muscles (Thirupathi et al. 2018). This study supports our previous study, and AuNPs might facilitate the tau`s entrance at the mitochondrial level.

Low levels of ROS production are crucial in the skeletal muscle since it is involved to carry out number of signaling during muscle adaptation and repairing. However, higher

Figure 3a

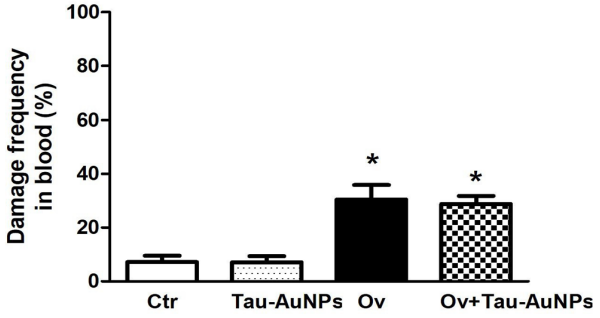


Figure 3b

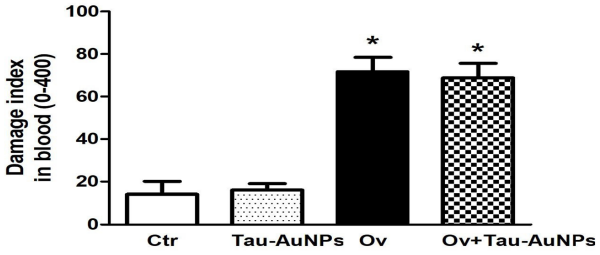


Figure 3. DNA damage in the blood of mice submitted to muscle overuse and Tau-AuNPs administration. The DNA damage frequency (a) and index (b) were expressed as the mean and SEM and were analyzed by one-way ANOVA followed by the post-hoc Bonferroni test. *p≤0.05 compared to the control and Tau-AuNPs. All statistical analyses were performed using Graph Pad Prism 7 software. Groups: control (Ctrl), tau-AuNPs, overuse (Ov), overuse plus tau-AuNPS (Ov+TauAuNPS).

levels of ROS production, on the other hand, can damage the components of cellular organs such as proteins and lipids resulting to changes in the muscular functions. Our group have reported that experimental overuse increased the ROS generation and subsequent oxidative damage (Thirupathi et al. 2018). The present study found that there was a significant difference in the overuse group that were not administrated with tau-AuNPs. However, tau-AuNPs administrated group did not show significant improvement in increasing sufhydryl level when compared to control. The possible reason is that the higher bound activity of AuNPs to thiol group of internal sulfur containing amino acids including homocysteine and cysteine may have disturbed the sulfhydryl levels (Bürgi 2015, Fenoglio et al. 2008). Moreover, the MDA level, a by-product of lipid peroxidation process, was increased with overuse muscles, whereas Tau-AuNPs decreased the MDA level. This result suggests a role of tau in the stabilization of muscle cells membrane from ROS insults. In addition, AuNPs have shown to dismutate superoxide radicals (Cao et al. 2011). AuNPs with other compounds increased the two-fold higher radical scavenging activity (Martín et al. 2010). The present results corroborated with the above findings that tau-AuNPs increased the ROS scavenging activity by reducing MDA level.

It is well established that increased ROS generation can lead to DNA damage. Tau has been reported to decrease the ROS generation through different mechanisms. However, the role of tau in protecting DNA from ROS induced oxidative damage is limited. We first time reported that tau-AuNPs role on protecting DNA damage in the overuse model. As we expected, the overuse group had increased index and frequency of DNA damage. However, unexpectedly overuse group administrated with Tau-AuNPs did not reduce the DNA damage frequency and index. Previous studies have reported that administration of tau decreased the DNA damage by reducing oxidative damages (Thirupathi et al. 2018, Sugiura et al. 2013). In contrast, AuNPs administration increased the DNA damage (Cardoso et al. 2014). However, the damage caused by AuNPs is depending on the size and administration duration of the nanoparticles (Cardoso et al. 2014, Berbeco et al. 2012). Our study corroborates with the above findings that tau alone had significant effect on reducing DNA damage, whereas the combination of Tau-AuNPs did not have significant

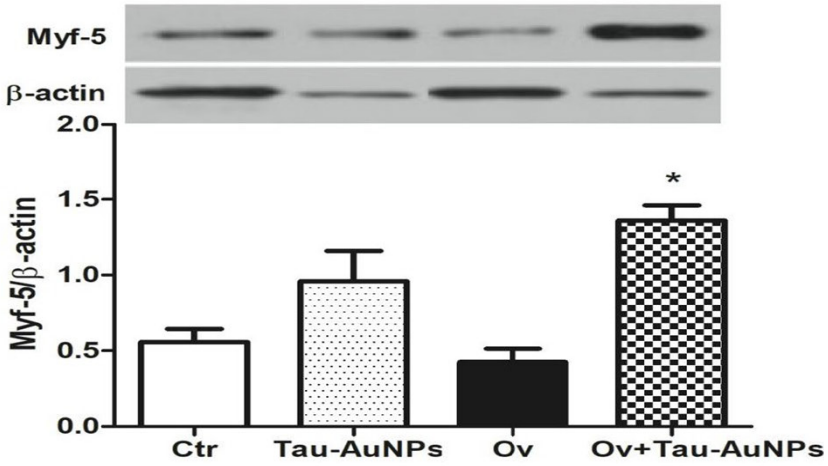


Figure 4. Muscle differentiation protein (Myf-5) of mice subjected to overuse exercise and Tau-AuNPs administration. The myf-5 level was increased in the Ov+Tau-AuNPS when compared to control and overuse animals. *p≤0.05 compared to the control and Tau-AuNPs. *p≤0.05 compared to the overuse.

improvements in the protection of DNA damage in the overuse model. The possible reason is that the AuNP may mitigate the effect of tau at the nuclear level for inducing DNA damage. However, different administration duration and size of the nanoparticles can impact the DNA damage.

The overuse of muscle and its consequent biochemical alterations are significantly influenced the muscle regeneration ability. The Myf-5 is an important muscle development protein belongs to myogenic regulatory factors. It is highly expressed in the activated muscle stem cells in early response to muscle injury. Studies have observed that tau plays a major role in the muscle regeneration through modulating calcium signaling pathways (Miyazaki et al. 2013) and regulating inflammatory mediators (Zhao et al. 2018, Nam et al. 2017). However, its role in regulating myogenic program is not well established. In this study, we reported first time that the role of tau-AuNPs on muscle recovery proteins in muscle overuse model. Recent study reported that AuNPs enhance the myogenic differentiation through p38 MAPK and promote the skeletal muscle regeneration (Ge et al. 2018). A study reported that tau mediated cytoprotection in the skeletal muscle (Uozumi et al. 2006). Our study supports with the above findings that tau-AuNPs increased the level of Myf-5 protein in the overuse model.

CONCLUSIONS

In conclusion, Tau-AuNPs can efficiently overcome the oxidative damage induced by muscle overuse. In addition, Tau-AuNPs influences the myogenic regulatory protein Myf-5 for improving muscle recovery of overuse model. However, Tau-AuNPs in reducing DNA damage was not significantly altered in the overuse animals, and this can be the limitation of this study. Overall, our results revealed an important role of the association of these molecules in mechanisms that regulate the muscle recovery.

Acknowledgments

The authors acknowledge the Universidade do Extremo Sul Catarinense (UNESC) for additional support.

REFERENCES

ARVIZO R, BHATTACHARYA R & MUKHERJEE P. 2010. Gold nanoparticles: Opportunities and Challenges in Nanomedicine. Expert Opin Drug Deliv 7: 753-763.

BERBECO RI, KORIDECK H, NGWA W, KUMAR R, PATEL J, SRIDHAR S, JOHNSON S, PRICE BD, KIMMELMAN A & MAKRIGIORGOS GM. 2012. DNA damage enhancement from gold nanoparticles for clinical MV photon beams. Radiat Res 178: 604-608.

BRADFORD MM. 1976. A rapid and sensitive method for the quantitation of microgram quantities of protein utilizing the principle of protein-dye binding. Anal Biochem 72: 248-254.

BROWN DI & GRIENDLING KK. 2015. Regulation of signal transduction by reactive oxygen species in the cardiovascular system. Circ Res 116: 531-549.

BÜRGI T. 2015. Properties of the gold-sulphur interface: from self-assembled monolayers to clusters. Nanoscale 7: 15553-15567.

CAO R, VILLALONGA R, DÍAZ-GARCÍA AM, CAO R, ROJO T & RODRÍGUEZ-ARGÜELLES MC. 2011. Gold nanoparticles enhancing dismutation of superoxide radical by its bis(dithiocarbamato) copper(II) shell. Inorg Chem 50: 4705-4712.

CARDOSO E ET AL. 2014. Acute and chronic administration of gold nanoparticles cause DNA damage in the cerebral cortex adult rats. Mutat Res 766-767: 25-30.

COLLINS A, DUSINSKÁ M, FRANKLIN M, SOMOROVSKÁ M, PETROVSKÁ H, DUTHIE S, LAURENCE F, MIHALIS P, KATARINA R & NICHOLAS V. 1997. Comet assay in human biomonitoring studies: reliability, validation, and applications. Environ Mol Mutagen 30: 139-146.

DANIEL MC & ASTRUC D. 2004. Gold nanoparticles: assembly, supramolecular chemistry, quantum-size-related properties, and applications toward biology, catalysis, and nanotechnology. Chem Rev 104: 293-346.

DA SILVA LA ET AL. 2014. Effects of taurine supplementation following eccentric exercise in young adults. Appl Physiol Nutr Metab 39: 101-104.

DIFIORI JP, BENJAMIN HJ, BRENNER J, GREGORY A, JAYANTHI N, LANDRY GL & LUKE A. 2014. Overuse injuries and burnout in youth sports: a position statement from the American Medical Society for Sports Medicine. Clin J Sport Med 24: 3-20.

ELLMAN GL. 1959. Tissue sulfhydryl groups. Arch Biochem Biophys 82: 70-77.

FENOGLIO I, CORAZZARI, FRANCIA S, BODOARDO & FUBINI B. 2008. The oxidation of glutathione by cobalt/tungsten carbide contributes to hard metal-induced oxidative stress. Free Radic Res 42: 737-745.

GE J, LIU K, NIU W, CHEN M, WANG M, XUE Y, GAO C, MA PX & LEI B. 2018. Gold and gold-silver alloy nanoparticles enhance the myogenic differentiation of myoblasts through p38 MAPK signaling pathway and promote in vivo skeletal muscle regeneration. Biomaterials 175: 19-29.

GROTTO D, SANTA MARIA LD, BOEIRA S, VALENTINI J, CHARÃO MF, MORO AM, NASCIMENTO PC, POMBLUM VJ & GARCIA SC. 2007. Rapid quantification of malondialdehyde in plasma by high performance liquid chromatography–visible detection. J Pharmaceut Biomed 43: 619-624.

GROVE RQ & KARPOWICZ SJ. 2017. Reaction of hypotaurine or taurine with superoxide produces the organic peroxysulfonic acid peroxytaurine. Free Radic Biol Med 108: 575-584.

JIN SE, BAE JW & HONG S. 2010. Multiscale observation of biological interactions of nanocarriers: From nano to macro. Microsc Res Tech 73: 813-823.

JONG CJ, AZUMA J & SCHAFFER S. 2012. Mechanism underlying the antioxidant activity of taurine: prevention of mitochondrial oxidant production. Amino Acids 42: 2223-2232.

LEVY R, THANH NT, DOTY RC, HUSSAIN I, NICHOLS RJ, SCHIFFRIN DJ, BRUST M & FERNIG DG. 2004. Rational and combinatorial design of peptide capping ligands for gold nanoparticles. J Am Chem Soc 126: 10076-10084.

MARTÍN R, MENCHÓN C, APOSTOLOVA N, VICTOR VM, ALVARO M, HERANCE JR & GARCÍA H. 2010. Nano-jewels in biology Gold and platinum on diamond nanoparticles as antioxidant systems against cellular oxidative stress. ACS Nano 4: 6957-6965.

MCLEAY Y, STANNARD S & BARNES M. 2017. The Effect of Taurine on the Recovery from Eccentric Exercise-Induced Muscle Damage in Males. Antioxidants (Basel) 6: E79.

MCLEAY Y, STANNARD S, HOULTHAM S & STARCK C. 2017. Dietary thiols in exercise: oxidative stress defence, exercise performance, and adaptation. J Int Soc Sports Nutr 14: 12.

MIYAZAKI T, HONDA A, IKEGAMI T & MATSUZAKI Y. 2013. The role of taurine on skeletal muscle cell differentiation. Adv Exp Med Biol 776: 321-328.

NAKAJIMA Y, OSUKA K, SEKI Y, GUPTA RC, HARA M, TAKAYASU M & WAKABAYASHI T. 2010. Taurine reduces inflammatory responses after spinal cord injury. J Neurotrauma 27: 403-410.

NAM SY, KIM HM & JEONG HJ. 2017. The potential protective role of taurine against experimental allergic inflammation. Life Sci 184: 18-24.

OSTJEN CA, ROSA CGS, HARTMANN RM, SCHEMITT EG, COLARES JR & MARRONI NP. 2018. Anti-inflammatory and antioxidant effect of melatonin on recovery from muscular trauma induced in rats. Exp Mol Pathol 106: 52-59.

PAULA MM ET AL. 2015. SILVEIRA PC & PINHO RA. 2015. Gold nanoparticles and/or N-acetylcysteine mediate

carrageenan-induced inflammation and oxidative stress in a concentration-dependent manner. J Biomed Mater Res A 103: 3323-3330.

POWERS SK, JI LL, KAVAZIS AN & JACKSON MJ. 2011. Reactive oxygen species: Impact on skeletal muscle. Compr Physiol 1: 941-969.

SAKELLARIOU GK, PEARSON T, LIGHTFOOT AP, NYE GA, WELLS N, GIAKOUMAKI II, GRIFFITHS RD, MCARDLE A & JACKSON MJ. 2016. Long-term administration of the mitochondria-targeted antioxidant mitoquinonemesylate fails to attenuate age-related oxidative damage or rescue the loss of muscle mass and function associated with aging of skeletal muscle. FASEB J 30: 3771-3785.

SCHAFFER SW, JONG CJ, RAMILA KC & AZUMA J. 2010. Physiological roles of taurine in heart and muscle. J Biomed Sci 17: S2.

SEIDEL U, HUEBBE P & RIMBACH G. 2018. Taurine: A Regulator of Cellular Redox Homeostasis and Skeletal Muscle Function. Mol Nutr Food Res 63(16): e1800569.

SILVA LA, PINHO CA, SILVEIRA PCL, TUON T, DE SOUZA CT, DAL-PIZZOL F & PINHO RA. 2010. Vitamin e supplementation decreases muscular and oxidative damage but not inflammatory response induced by eccentric contraction. J Physiol Sci 60: 51-57.

SUGIURA H, OKITA S, KATO T, NAKA T, KAWANISHI S, OHNISHI S, OSHIDA Y & MA N. 2013. Protection by taurine against INOS-dependent DNA damage in heavily exercised skeletal muscle by inhibition of the NF-κB signaling pathway. Adv Exp Med Biol 775: 237-246.

THIRUPATHI A ET AL. 2018. Modulatory effects of taurine on metabolic and oxidative stress parameters in a mice model of muscle overuse. Nutrition 54: 158-164.

TICE RR, AGURELL E, ANDERSON D, BURLINSON B, HARTMANN A, KOBAYASHI H, MIYAMAE Y, ROJAS E, RYU JC & SASAKI YF. 2000. Single cell gel/Comet Assay: guidelines for in vitro and in vivo genetic toxicology testing. Environ Mol Mutagen 35: 206-221.

TOMA HE, TOMA VM, SERGIO H & ARAKI K. 2010. The coordination chemistry at gold nanoparticles. J Braz Chem Soc 21: 1158-1176.

UOZUMI Y, IT T, HOSHINO Y, MOHRI T, MAEDA M, TAKAHASHI K, FUJIO Y & AZUMA J. 2006. Myogenic differentiation induces taurine transporter in association with taurine-mediated cytoprotection in skeletal muscles. Biochem J 394: 699-706.

VICTOR EG, SILVEIRA PC, POSSATO JC, DA ROSA GL, MUNARI UB, DE SOUZA CT, PINHO RA, DA SILVA L, STRECK EL & PAULA MM. 2012. Pulsed ultrasound associated with gold nanoparticle gel reduces oxidative stress parameters and expression of pro-inflammatory molecules in an animal model of muscle injury. J Nanobiotechnol 12: 10-11.

ZHANG Z, LIU D, YI B, LIAO Z, TANG L, YIN D & HE M. 2014. Taurine supplementation reduces oxidative stress and protects the liver in an iron-overload murine model. Mol Med Rep 10: 2255-2262.

ZHAO H, QU J, LI Q, CUI M, WANG J, ZHANG K, LIU X, FENG H & CHEN Y. 2018. Taurine supplementation reduces neuroinflammation and protects against white matter injury after intracerebral hemorrhage in rats. Amino Acids 50: 439-451.

How to cite

THIRUPATHI A, SORATO HR, SILVA PRL, DAMIANI AP, ANDRADE VM, SILVEIRA PCL, NESI RT, PAULA MMS & PINHO RA. 2021. Effect of taurine associated gold nanoparticles on oxidative stress in muscle of mice exposed to overuse model. An Acad Bras Cienc 93: e20191450. DOI 10.1590/0001-3765202120191450.

Manuscript received on November 25, 2019;
accepted for publication on February 5, 2020

ANAND THIRUPATHI[1]
https://orcid.org/0000-0002-0924-2538

HELEN R. SORATO[2]
https://orcid.org/0000-0002-0592-7337

PAULO R.L. SILVA[2]
https://orcid.org/0000-0001-7787-8530

ADRIANI P. DAMIANI[3]
https://orcid.org/0000-0002-2908-7125

VANESSA M. ANDRADE[3]
https://orcid.org/0000-0002-8474-4482

PAULO C.L. SILVEIRA[2]
https://orcid.org/0000-0003-4908-2257

RENATA T. NESI[5]
https://orcid.org/0000-0002-6774-0893

MARCOS M.S. PAULA[4]
https://orcid.org/0000-0003-1383-9174

RICARDO A. PINHO[5]
https://orcid.org/0000-0003-3116-4553

[1]Faculty of Sports Science, Ningbo University, Ningbo 315211, China

[2]Laboratório de Fisiopatologia Experimental, Programa de Pós-Graduação em Ciências da Saúde, Unidade de Ciências da Saúde, Universidade do Extremo Sul Catarinense, 88806-000 Criciúma, SC, Brazil

[3]Laboratório de Biologia Molecular e Celular, Programa de Pós-Graduação em Ciências da Saúde, Unidade de Ciências da Saúde, Universidade do Extremo Sul Catarinense, 88806-000 Criciúma, SC, Brazil

[4]Programa de Pós-Graduação em Ciência e Engenharia de Materiais, Universidade Federal do Amazonas, 69077-000 Manaus, AM, Brazil

[5]Laboratório de Bioquímica do Exercício em Saúde, Programa de Pós-Graduação em Ciências da Saúde, Faculdade de Medicina, Rua Imaculada Conceição, 155, Pontifícia Universidade Católica do Paraná, 80215-901 Curitiba, PR, Brazil

Correspondence to: **Anand Thirupathi**
E-mail: ananthzeal@gmail.com

Author contributions

Anand Thirupathi wrote the manuscript and reviewed and edited the final version of the manuscript. Helen R. Sorato, Paulo R.L. Silva and Adriani P. Damiani performed the experiment and statistical analysis of the data. Vanessa M. Andrade reviewed and edited the manuscript. Paulo C.L. Silveira and Renata T. Nesi contributed to write the manuscript and supervised the experimental data. Marcos M.S. Paula reviewed and edited the final version of the manuscript. Ricardo A. Pinho conceived the idea, obtained the financial resource for this project, and wrote the manuscript. All the authors approved the final version of the manuscript.