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Subchronic nandrolone administration reduces cardiac oxidative markers during restraint stress by modulating protein expression patterns

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19

20

1 **Abstract**

2 Nandrolone decanoate (ND), an anabolic-androgenic steroid prohibited in collegiate and
3 professional sports, is associated with detrimental cardiovascular effects through redox-dependent
4 mechanisms. We previously observed that high-dose short-term ND administration (15 mg/kg for 2
5 weeks) did not induce left heart ventricular hypertrophy and, paradoxically, improved postischemic
6 response, whereas chronic ND treatment (5 mg/kg twice a week for 10 weeks) significantly reduced
7 the cardioprotective effect of postconditioning, with an increase in infarct size and a decrease in
8 cardiac performance.

9 We wanted to determine whether short-term ND administration could affect the oxidative redox
10 status in animals exposed to acute restraint stress. Our hypothesis was that, depending on treatment
11 schedule, ND may have a double-edged sword effect.

12 Measurement of malondialdehyde and 4-hydroxynonenal, two oxidative stress markers, in rat
13 plasma and left heart ventricular tissue, revealed that the levels of both markers were increased in
14 animals exposed to restraint stress, whereas no increase in marker levels was noted in animals
15 pretreated with ND, indicating a possible protective action of ND against stress-induced oxidative
16 damage. Furthermore, isolation and identification of proteins extracted from the left heart
17 ventricular tissue samples of rats pretreated or not with ND and exposed to acute stress showed a
18 prevalent expression of enzymes involved in amino acid synthesis and energy metabolism. Among
19 other proteins, peroxiredoxin 6 and alpha B-crystallin, both involved in the oxidative stress
20 response, were predominantly expressed in the left heart ventricular tissues of the ND-pretreated
21 rats.

22 In conclusion, ND seems to reduce oxidative stress by inducing the expression of antioxidant
23 proteins in the hearts of restraint-stressed animals, thus contributing to amelioration of postischemic
24 heart performance.

25

26 **Keywords:** anabolic-androgenic steroids; heart; proteomics; oxidative stress; restraint stress

27

28 **Introduction**

29 Anabolic-androgenic steroids (AASs), synthetic derivatives of testosterone, exert both androgenic
30 and anabolic actions [1] through their binding to the androgen receptor, acting at both the genomic
31 and non genomic levels. AAS abuse, because of their anabolic effects, is detrimental to health [2-5];
32 nonetheless, AASs are widely used by athletes to increase muscle mass and power or enhance
33 physical endurance [6]. Human and animal studies have reported discordant results regarding the
34 cardiac and metabolic complications of AAS abuse [5,7-11], with some suggesting that testosterone

1 improves myocardial lipid metabolism [12] and may act as a cardioprotectant and coronary
2 vasodilator comparable to conventional anti-ischemic drugs [13,14].

3 In cardiovascular diseases, both protective and damaging mechanisms derive from redox
4 conditions. For example, exercise protects the heart by increasing myocardial resistance to
5 ischemia-reperfusion (I/R) injury [15,16]. Yet, as a consequence of I/R injury, myocardial redox
6 status is altered because of increased reactive oxygen species (ROS) production . This effect can be
7 counteracted by exercise, which improves antioxidant defenses and reduces infarct size [15-17].

8 Nandrolone decanoate (ND), one of the most extensively studied AASs, may interfere with redox
9 conditions [18] and its abuse can limit the cardioprotective effects of exercise. Indeed, chronic ND
10 administration for 6 to 10 weeks at supraphysiological doses causes heart hypertrophy [19-21],
11 increases cardiac susceptibility to I/R injury [17,22,23], activates the local renin-angiotensin system
12 [24], and induces ventricular repolarization disturbances [25].

13 In two previous studies we reported that subchronic treatment with high-dose ND (15 mg/kg for 14
14 days) does not induce evident left ventricular hypertrophy but, paradoxically, improves cardiac
15 postischemic response [26], whereas chronic ND treatment (10 weeks) significantly reduces the
16 cardioprotective effect of postconditioning, with an increase in infarct size and decrease in cardiac
17 performance [27]. We hypothesized that the double-edged sword effect of ND may be related to
18 treatment schedule and redox conditions. To test this hypothesis, we investigated the effects of
19 subchronic ND treatment on left heart ventricular tissue and on systemic and cardiac redox status in
20 rats exposed or not to restraint stress. Experimental evidence supports the notion that stressful
21 conditions produce oxidative damage and the rationale for using restraint to investigate alterations
22 in redox activities in different tissues. Restraint conditions have been associated with impairment of
23 antioxidant enzyme activity (e.g., superoxide dismutase) and depletion of reduced glutathione
24 [28,29]. Moreover, we previously reported that restraint conditions induce downregulation of
25 myocardial contractility response to isoproterenol stimulation which is reversed by ND pretreatment
26 [30].

27 In this experimental model of subchronic ND treatment in modulating redox status, we measured
28 two oxidative stress markers in plasma and left heart ventricular tissue samples: malondialdehyde
29 (MDA) and 4-hydroxynonenal (4-HNE), the aldehydes resulting from polyunsaturated fatty acid
30 lipid peroxidation. Using a proteomic approach, we identified the protein profile signatures in the
31 left heart ventricular tissues of rats pretreated or not with ND and exposed to acute restraint stress .

32

33 **Methods**

34 **Animals and treatments**

1 Treatment schedule: 70 two-month-old male Sprague–Dawley rats weighing 300 g (Harlan
2 Laboratories, San Pietro al Natisone, Udine, Italy) were housed in groups of two in polycarbonate
3 cages with ad libitum access to food and tap water and maintained in a controlled environment
4 (12:12 light–dark cycle, room temperature 20-24° C, and humidity 50-60%). They were allowed 1
5 week of acclimatization before the experiment began and were handled daily during this period. To
6 avoid circadian variability, all tests were performed between 10:00 and 12:00, when plasma
7 hormones levels are relatively low. Institutional ethical committee approval was obtained for this
8 study; all experimental procedures were performed in accordance with EC Directive 86/609/EEC
9 and Italian law regulating experiments on animals.

10 One group of rats (n=32) received once a day for 14 days an intramuscular (i.m.) injection of 0.5
11 mL of peanut oil (vehicle) containing 15 mg/kg of ND (DECA-Durabolin®, Organon), which is
12 equivalent to the abuse dose of AAS in humans [31]. Sixteen of these rats (ND group) remained in
13 their cages until sacrifice, and the 16 other animals were exposed to 1 h of restraint stress 24 h after
14 the last injection and immediately before sacrifice (ND+S group) [32]. A second group (n=32)
15 received 0.5 mL peanut oil i.m. injection once a day for 14 days. This group was divided into two
16 subgroups: 16 were treated with the vehicle only (V group) and were sacrificed, and the 16 other
17 animals were exposed to the same acute restraint stress protocol described above (V+S group). The
18 control group (n=6) received i.m. injections of normal saline solution daily for 14 days to check for
19 possible peanut oil effects. The experimental design is presented in Table 1. At the end of 14 days
20 of treatment, all animals were sacrificed by decapitation and trunk blood was collected. The hearts
21 were rapidly removed, rinsed with saline buffer solution, and dissected to collect the left heart
22 ventricle. All samples were snap frozen and stored at -80° C until use.

23

24 **Oxidative stress marker measurement in plasma and left heart ventricles**

25 Plasma oxidative stress damage was determined by measuring the fluorescent adducts formed
26 between lipid peroxidation-derived aldehydes and plasma proteins. Plasma samples were extracted
27 in ethanol/ether (3:1 v/v) and then centrifuged at 1000 g for 10 min. Pellets were resuspended in
28 ethanol/ether (3:1 v/v); this procedure was repeated three times. Protein adducts were dried under
29 nitrogen and resuspended in a 5% SDS solution. Hydroxynoneal (4-HNE) protein adducts (355 nm
30 excitation/460 nm emission) and malondialdehyde (MDA) protein adducts (390 nm excitation/460
31 nm emission) were measured using a spectrofluorometer (SFM 25 Kontron Instruments AG,
32 Zurich, Switzerland). Data are expressed as arbitrary unit fluorescence (AUF)/mg plasma proteins
33 [33].

1 In the left heart ventricle lysates, free MDA levels were determined by measuring thiobarbituric
2 acid-reactive substances [34]. Briefly, left heart ventricle tissues were disintegrated with a Mikro-
3 Dismembrator II (B. Braun, Melsungen, Germany) and dissolved in Tris-HCl buffer (0.1 M, pH
4 7.4) using a Potter-Elvehjem homogenizer (Sigma-Aldrich, St. Louis, MO, USA) The MDA
5 concentrations determined by the thiobarbituric acid reaction are expressed as nmol/g tissue.

7 **Tissue damage evaluation**

8 Tissue damage was evaluated by measuring two cytotoxic markers, lactate dehydrogenase (LDH)
9 (Abbott Laboratories, Abbott Park, IL, USA, 2P56-21) and creatine kinase MB isozyme (CK-MB)
10 (Abbott, 6K25-30), in blood samples according to the manufacturer's instructions with the aid of a
11 clinical chemistry analyzer (Abbott, Architect C8000 Plus).

13 **Protein sample preparation**

14 Frozen left heart ventricular tissue samples were disintegrated with a Mikro-Dismembrator II and
15 lysed in RIPA buffer (20 mM HEPES, 150 mM NaCl, 5m M EDTA, 1 mM DTT, 1% Triton X-100,
16 10% glycerol, 1 µg/mL leupeptin, 1 µg/mL aprotinin, 1 µg/mL phenylmethyl-sulfonyl fluoride, 1
17 mM sodium orthovanadate) at 4° C. The lysates were then spun-down to remove insoluble cellular
18 debris. Protein concentration was measured by the Lowry method [35].

20 **Two-dimensional gel electrophoresis (2-DE)**

21 Two-dimensional gel electrophoresis (2-DE) was performed according to the manufacturer's
22 instructions (GE Healthcare, Milan, Italy) with slight modifications. Samples containing 0.125 mg
23 proteins were in-gel rehydrated for 12 h onto 7-cm immobilized non-linear pH gradient strips (pH
24 3-10), electrofocused at 200 V, 500 V, and 1000 V each for 1 h (step-N-hold), 1000-5000 V
25 (gradient) for 30 min, and 5000 V (step-N-hold) for 3 h using an IPGphor system (GE Healthcare).
26 The strips were then reduced for 30 min in SDS equilibration buffer (50 mM Tris-HCl pH 8.8, 6 M
27 urea, 30% glycerol, 2% SDS) containing 1% (w/v) DTT, followed by 30 min alkylation in the same
28 equilibration buffer with 2.5% (w/v) iodoacetamide instead of DTT. Electrophoresis was run on an
29 Ettan DALT II system (GE Healthcare). The gels were stained with colloidal Coomassie Blue G250
30 (Bio-Rad, Hercules, CA, USA), scanned using image scanner and the gel images were analyzed
31 with ImageMaster 2D Platinum 6.0 software (GE Healthcare).

33 **Mass spectrometry and protein identification**

1 Protein spots were excised and in-gel trypsin (Sigma-Aldrich) digested according to the
2 manufacturer's instructions. Aliquots of 1 μ L of each sample were mixed with an equal volume of
3 matrix (α -cyano-4-hydroxycinnamic acid), saturated in 50% acetonitrile (Sigma Aldrich), and the
4 mixture was dropped onto the metal target plate of a Microflex LRF MALDI-TOF mass
5 spectrometer (Bruker Daltonics, Germany). Mass spectrometry analysis was carried out in reflector
6 mode. The adrenocorticotrophic hormone (2464.1989 m/z) and the angiotensin II fragments
7 (1045.5423 m/z) were used for internal mass calibration to maximize mass accuracy. The peptide
8 mass fingerprint spectra were searched against the MASCOT (Matrix Science) and National Center
9 for Biotechnology Information (NCBI, www.ncbi.nlm.gov) protein databases.

10

11 **Western blot analysis (WB)**

12 Total cellular proteins (25 μ g) were resolved by 10% SDS-PAGE and transferred onto
13 nitrocellulose membrane (HybondTM ECLTM, GE Healthcare) for immunoblotting. The membranes
14 were probed **with the following antibodies: rabbit polyclonal anti-glutathione-S-transferase (GST)**
15 **(1:2000, Alpha Diagnostic International, San Antonio, TX, USA, GSTM11-S)**, rabbit monoclonal
16 anti-CRYAB (1:5000, GeneTex, Irvine CA, USA, GTX62094), rabbit monoclonal anti-PRDX6
17 (1:1000, GeneTex GTX62281), mouse monoclonal anti-alpha tubulin (TUB) (1:10000, Santa Cruz
18 Biotechnology, Dallas, TX, USA, SC-23948) and **goat polyclonal anti-vinculin (VCL) (1:1000,**
19 **Santa Cruz Biotechnology sc-7649)**. **The blots were then incubated** with their appropriate secondary
20 antibodies. Protein signals were detected using enhanced chemiluminescence ECLTM WB detection
21 reagents (GE Healthcare). WB images were analyzed using ImageJ software
22 (<http://imagej.nih.gov/ij/>). CRYAB and PRDX6 were quantified by normalizing them against TUB
23 selected as the reference housekeeping protein; **GST was normalized using VCL.**

24

25 **Statistical analysis**

26 All data are presented as the mean and the median as a central measure and interquartile range
27 (IQR) as a measure of spread. The Shapiro-Wilk test was applied to check the normality
28 assumption. Since the MDA concentrations in the left heart ventricular tissue samples had skewed
29 distribution, natural log transformation was applied to achieve normality assumption for standard
30 parametric analysis. Two-way analysis of variance (ANOVA) and Tukey's post hoc test were
31 carried out in the event of a significant F ratio. Statistical significance was set at $p < 0.05$. Analyses
32 were performed using R version 3.02 (www.r-project.org).

33

34 **Results**

1 **Nandrolone prevents HNE and MDA accumulation**

2 We measured HNE and MDA adducts in plasma and MDA in its free form in left heart ventricular
3 specimens. Since HNE is quickly metabolized to less cytotoxic compounds in many tissues, and
4 thus scantily detectable by photometric methods, we measured in left heart ventricular tissue
5 samples the protein expression levels of GST, an enzyme involved in its detoxification. Indeed,
6 through GST, HNE is rapidly and covalently conjugated to GSH, giving rise to GSH-HNE, which is
7 more water soluble and thus more easily excreted.

8 A significant increase in the plasma levels of both HNE and MDA adducts was observed in the rats
9 exposed to restraint stress (Fig. 1 and Table 2; $p=0.04$ and $p=0.02$, respectively). The aldehyde-
10 protein adduct levels were lower in the ND+S group than in the V+S group, suggesting that ND
11 may prevent against restraint-induced stress effects. However, two-way ANOVA found no
12 significant interaction (Table 2). MDA in its free form in the left heart ventricular tissues was
13 increased in the vehicle-treated group exposed to restraint stress (V vs V+S, $p=0.002$), whereas the
14 stress-induced MDA increase was significantly lower in the ND+S group (Fig. 2).

15 Western blotting indicated a significant increase in GST protein levels after ND treatment in the left
16 heart ventricular tissue samples from animals exposed or not to restraint stress, as compared to the
17 tissues from animals that had not received ND (V and V+S groups) (Fig. 3).

18 The MDA levels in the control group and the V group were similar (data not shown).

20 **Nandrolone treatment impairs blood LDH and CK-MB activity levels**

21 HNE and MDA are highly toxic side products of lipid peroxidation. To determine whether these
22 catabolites might have damaged or altered heart muscle viability, we evaluated the activity of
23 lactate dehydrogenase (LDH), a classic indicator of tissue cytotoxicity, and creatine kinase MB
24 isozyme (CK-MB), a cardiac-specific cytotoxicity marker. LDH and CK-MB levels were increased
25 in the control group exposed to restraint stress as compared to the unstressed group (V vs. V+S
26 groups), though the difference between-groups was not statistically significant. Interestingly, LDH
27 and CK-MB levels were significantly lower in both ND-treated groups than in the control group
28 exposed to restraint stress (V+S) (Fig. 4). Overall, these data strengthen the hypothesis that the
29 changes in oxidative stress after exposure to restraint stress did not damage heart muscle integrity.

31 **Left heart ventricular tissue from V+S and ND+S animals displays different proteomic** 32 **signatures**

33 To gain further insights into the molecular components involved in triggering differential responses
34 to ND treatment in the animals exposed to restraint stress, 2-DE was performed on lysates of left

1 heart ventricular tissue samples from both groups (V+S and ND+S). Representative images are
2 shown in Fig.5. Comparison between the two groups showed a higher number of protein spots in
3 the ND+S than in the V+S samples (282 spots in ND+S vs 201 spots in V+S), especially within the
4 range of 20-45 kDa. Eighty-five visible spots were manually excised from the gels and subjected to
5 MALDI-TOF-MS analysis to identify the corresponding proteins. The spots unambiguously
6 identified via MALDI-TOF-MS are numbered in Fig. 5 and the proteins identified (together with
7 their relative scores, sequence coverage, and functional categories) are reported in Table 3. Several
8 spots were identified by MALDI-TOF-MS analysis as being either different isoforms of the same
9 protein or the same protein that migrated differently in other cases, suggesting post-translational
10 modifications. Functional category analysis highlighted that the proteins involved in energy
11 metabolism were the major components detected.

12 We identified three non-overlapping spots detectable only in the protein profile of the left heart
13 ventricular tissue samples from the ND+S group. Mass spectrometry analysis identified these spots
14 as succinyl-CoA transferase, alpha B-crystallin (CRYAB), and peroxiredoxin 6 (PRDX6), the last
15 two of which are involved in cellular response to oxidative stress [36,37]. Indeed, CRYAB is a
16 chaperone protein that prevents apoptosis induced by OS and PRDX6 protects against oxidative
17 injury through its peroxidase activity.

18 These data were corroborated by WB analysis carried-out onof left heart ventricular tissue samples
19 from the four groups (V, V+S, ND, ND+S). The comparison showed that PRDX6 expression levels
20 were higher in both ND-treated groups, whether exposed to restraint stress or not, whereas CRYAB
21 expression was increased in the two groups exposed to restraint stress, with a greater increase in the
22 ND-treated group (Fig. 6).

23

24 **Discussion**

25 Our findings indicate that restraint stress impacts on oxidative stress and that ND administration can
26 alter the oxidative status of cardiac tissue in rats exposed to restraint stress. Previous experimental
27 evidence has shown that short-term ND pretreatment can protect against pro-oxidant conditions,
28 such as I/R injury [26]; therefore, we hypothesized that it may exert a protective action against
29 oxidative stress. To settle this issue, and because stressful conditions have been found to cause
30 oxidative damage in diverse tissues, we employed an *in vivo* model in which rats were exposed to
31 restraint stress [28,29,38,39].

32 Our assumption seems to contrast with that of authors reporting a ND-mediated impairment of
33 exercise-induced cardioprotection [17,24,22,40]. A possible explanation for the protective effect of

1 ND we observed in left heart ventricular tissue is that ND exerts a differential effect in relation to
2 duration of treatment (14 days in our study vs 6 to 8 weeks in those mentioned above).

3 With the present study, we report that oxidative stress marker levels in plasma and left heart
4 ventricular tissues are increased in rats exposed to restraint stress. Although ND *per se* does not
5 directly modify oxidative stress markers, it appears to prevent an increase in free MDA in the left
6 heart ventricular tissue of restrained animals and that it enables HNE detoxification by means of
7 increased levels of GST. This observation is shared by previous results reporting that ND enhances
8 GST activity [41]. A similar trend was observed for the accumulation of HNE and MDA adducts in
9 the plasma samples. The lack of significant differences between the oxidative stress marker levels
10 in the plasma samples may be due to several reasons; indeed, it cannot be ruled out that oxidative
11 stress varies in different tissues of the body. Two data sets indicate restraint stress-induced lipid
12 peroxidation: the increased HNE and MDA levels and the appreciable, though statistically not
13 significant, blood accumulation of LDH and CK-MB detected in the V+S group.

14 Overall, the data indicate that, albeit restraint stress led to oxidative damage, it apparently does not
15 affect tissue viability. Interestingly, the opposite behavior of the oxidative stress and cytotoxic
16 markers detected in the ND+S group suggests that ND plays a protective role against the negative
17 effects of oxidative stress.

18 The effects of ND on oxidative stress in the animals exposed to restraint stress may be related to its
19 effect on the corticosterone (CORT) response to stressful conditions. In a previous study, we
20 reported that in rats that received ND treatment identical to the schedule used in the present study
21 CORT levels were reduced in both basal condition and after stress exposure [42]. Indeed,
22 glucocorticoids may affect the redox status of different tissues (e.g., endothelial cells and brain) via
23 different mechanisms, including an increase in superoxide cell production and impairment of tissue
24 antioxidant capacity [43,44]. Therefore, one can assume that the increase in the two oxidative stress
25 markers in the V+S group is a consequence of the high CORT levels induced by stress and because
26 ND decreases the CORT levels in plasma after stress, it could conceivably exert a protective action
27 against oxidative stress.

28 We identified two additional novel players implicated in oxidative stress response to subchronic ND
29 pretreatment: CRYAB and PRDX6. These two proteins, which were expressed at higher levels in
30 the ND+S as compared to the V+S samples, are both involved in oxidative response. PRDX6, a
31 class of thiol-specific antioxidant enzymes, exerts peroxidase activity against a broad range of
32 peroxides [36,45-47]. CRYAB is activated by phosphorylation during oxidative stress, thus
33 protecting cells from apoptosis induced by oxidative damage [48-50]. Previous studies have shown
34 that transgenic mice that ubiquitously overexpress CRYAB have increased tolerance to I/R injury

1 [51], whereas CRYAB/HSPB2-null mouse hearts display poorer functional recovery, a higher cell
2 death rate [52], increased stiffness, and, hence, poor myocardial relaxation following I/R injury [53]
3 as compared with wild-type controls. Of note, we previously observed an improvement in
4 postischemic diastolic and systolic cardiac functions after subchronic ND treatment [26].
5 To elucidate to what extent the effect on PRDX6 and CRYAB expression was due to ND
6 administration by itself or ND coupled to stress, we compared their expression in samples from the
7 four groups (V, V+S, ND, ND+S) by WB analysis. ND treatment alone was enough to induce up-
8 modulation of both PRDX6 and CRYAB.

9 We previously reported that subchronic ND treatment improves systolic function induced by
10 postconditioning cardioprotection via β 2-adrenoreceptor activation [26] and probably, via the same
11 pathway, prevents the decrease induced by restraint stress in heart contractile response to
12 isoproterenol [30]. These findings appear to be in line with results from studies on other antioxidant
13 substances [54,55]. Vitamin C is known to enhance the positive inotropic response to the β 1-
14 adrenoreceptor agonist dobutamine in the presence of high levels of reactive oxygen species [54]
15 and, in the same condition, the free radical scavenger N-acetylcysteine was found to strengthen the
16 inotropic effect of dobutamine in isolated heart tissue [55]. In our experimental conditions, it is
17 unlikely that ND had a direct antioxidant action. ND-pretreatment affects the protein expression
18 patterns, as revealed by 2-DE mapping.

19 In conclusion, our study provides further evidence for an enhanced oxidative response in animals
20 exposed to restraint stress and reports the novel observation that subchronic ND-pretreatment limits
21 myocardial redox response induced by restraint *via* the modification of anti-oxidant protein
22 expression. These effects may explain the amelioration of postischemic heart performance observed
23 after ND administration [26]. It can be argued that ND acts as a double-edged sword, with positive
24 or negative effects on the heart depending on the treatment schedule.

25

26 **Conflict of interest**

27 The Authors declare that they have no conflict of interest.

28

29

References

1. Kicman AT (2008) Pharmacology of anabolic steroids. *Br J Pharmacol* 154:502-521. doi:10.1038/bjp.2008.165
2. Nieschlag E, Vorona E (2015) MECHANISMS IN ENDOCRINOLOGY: Medical consequences of doping with anabolic androgenic steroids: effects on reproductive functions. *Eur J Endocrinol* 173:R47-R58. doi:10.1530/EJE-15-0080
3. Nieschlag E, Vorona E (2015) Doping with anabolic androgenic steroids (AAS): Adverse effects on non-reproductive organs and functions. *Rev Endocr Metab Disord* 16:199-211. doi:10.1007/s11154-015-9320-5
4. Hartgens F, Kuipers H (2004) Effects of androgenic-anabolic steroids in athletes. *Sports Med* 34:513-554. doi:10.1112-164204/0008-0513/531.00/0
5. Turillazzi E, Perilli G, Di Paolo M, Neri M, Riezzo I, Fineschi V (2011) Side effects of AAS abuse: an overview. *Mini Rev Med Chem* 11:374-389
6. Bird SR, Goebel C, Burke LM, Greaves RF (2016) Doping in sport and exercise: anabolic, ergogenic, health and clinical issues. *Ann Clin Biochem* 53:196-221
7. Achar S, Rostamian A, Narayan SM (2010) Cardiac and metabolic effects of anabolic-androgenic steroid abuse on lipids, blood pressure, left ventricular dimensions, and rhythm. *Am J Cardiol* 106 (6):893-901. doi:10.1016/j.amjcard.2010.05.013
8. Vanberg P, Atar D (2010) Androgenic anabolic steroid abuse and the cardiovascular system. *Handb Exp Pharmacol* 195:411-457. doi:10.1007/978-3-540-79088-4_18.
9. Riezzo I, De Carlo D, Neri M, Nieddu A, Turillazzi E, Fineschi V (2011) Heart disease induced by AAS abuse, using experimental mice/rats models and the role of exercise-induced cardiotoxicity. *Mini Rev Med Chem* 11:409-424. doi:10.2174/138955711795445862
10. Vasilaki F, Tsitsimpikou C, Tsarouhas K, Germanakis I, Tzardi M, Kavvalakis M, Ozcagli E, Kouretas D, Tsatsakis AM (2016) Cardiotoxicity in rabbits after long-term nandrolone decanoate administration. *Toxicol Lett* 241:143-151
11. Nikolic TR, Zivkovic VI, Srejovic IM, Radovanovic DS, Jeremic NS, Jevdjevic MD, Djuric DM, Jakovljevic VL (2016) Acute effects of nandrolone decanoate on cardiodynamic parameters in isolated rat heart. *Can J Physiol Pharmacol* 94:1048-1057
12. Langfort J, Jagsz S, Dobrzyn P, Brzezinska Z, Klapcinska B, Galbo H (2010) Testosterone affects hormone-sensitive lipase (HSL) activity and lipid metabolism in the left ventricle. *Biochem Biophys Res Commun* 399:670-676. doi:10.1016/j.bbrc.2010.07.140
13. Liu J, Tsang S, Wong TM (2006) Testosterone is required for delayed cardioprotection and enhanced heat shock protein 70 expression induced by preconditioning. *Endocrinology* 147:4569-4577. doi:10.1210/en.2006-0297
14. Borst SE, Quinby JC, Yarrow JF, Conover CF, Powers SK (2010) Testosterone administration induces protection against global myocardial ischemia. *Horm Metab Res* 42:122-129. doi:10.1055/s-0029-1241843
15. Powers SK, Demirel HA, Vincent HK, Coombes JS, Naito H, Hamilton KL, Shanely RA, Jessup J (1998) Exercise training improves myocardial tolerance to in vivo ischemia-reperfusion in the rat. *Integrative and Comparative Physiology* 275:R1468-R1477
16. Hamilton KL, Powers SK, Sugiura T, Kim S, Lennon S, Tumer N, Mehta JL (2001) Short-term exercise training can improve myocardial tolerance to I/R without elevation in heat shock proteins. *Physiology* 281:H1346-H1352
17. Chaves E, Pereira PPJ, Fortunato RS, Masuda MO, de Carvalho AC, de Carvalho DP, Oliveira MF, Nascimento JH (2006) Nandrolone decanoate impairs exercise-induced cardioprotection: role of

1 antioxidant enzymes. Journal of steroid Biochemistry and Molecular Biology 99:223-230.
2 doi:org/10.1016/j.jsbmb.2006.01.004

3

4 18. Frankenfeld SP, Oliveira LP, Ortenzi VH, Rego-Monteiro IC, Chaves EA, Ferreira AC, Leitão AC, Carvalho
5 DP, Fortunato RS (2014) The anabolic androgenic steroid nandrolone decanoate disrupts redox
6 homeostasis in liver, heart and kidney of male Wistar rats. PLoS One 9 (9)

7 19. Tanno AP, das Neves VJ, Rosa KT, Cunha TS, Giordano FC, Calil CM, Guzzoni V, Fernandes T, de Oliveira
8 EM, Novaes PD, Irigoyen MC, Moura MJ, Marcondes FK (2011) Nandrolone and resistance training induce
9 heart remodeling: role of fetal genes

10 and implications for cardiac pathophysiology. Life Sci 89:631-637

11

12 20. Franquni JV, do Nascimento AM, de Lima EM, Brasil GA, Heringer OA, Cassaro KO, da Cunha TV, Musso
13 C, Silva Santos MC, Kalil IC, Endringer DC, Boëchat GA, Bissoli NS, de Andrade TU (2013) Nandrolone
14 decanoate determines cardiac remodelling and injury by an imbalance in cardiac inflammatory cytokines
15 and ACE activity, blunting of the Bezold-Jarisch reflex, resulting in the development of hypertension.
16 Steroids 78:379-385

17

18 21. Frati P, Busardò FP, Cipolloni L, Dominicis ED, Fineschi V (2015) Anabolic Androgenic Steroid (AAS)
19 related deaths: autoptic, histopathological and

20 toxicological findings. Curr Neuropharmacol Jan;(1):146-59 13:146-159

21 22. Chaves EA, Fortunato RS, Carvalho DP, Hamilton KL, Nascimento JH, Oliveira MF (2013) Exercise-
22 induced cardioprotection is impaired by anabolic steroid treatment through a redox-dependent
23 mechanism. J Steroid Biochem Mol Biol 138:267-272. doi:10.1016/j.jsbmb.2013.06.006

24 23. Du Toit EF, Rossouw E, Van Rooyen J, Lochner A (2005) Proposed mechanisms for the anabolic steroid-
25 induced increase in myocardial susceptibility to ischaemia/reperfusion injury. CARDIOVASCULAR JOURNAL
26 OF SOUTH AFRICA 16:21-28

27 24. Rocha FL, Carmo EC, Roque FR, Hashimoto NY, Rossoni LV, Frimm C, Aneas I, Negrão CE, Krieger JE,
28 Oliveira EM (2007) Anabolic steroids induce cardiac renin-angiotensin system and impair the beneficial
29 effects of aerobic training in rats. Am J Physiol Heart Circ Physiol 293:H3575-H3583.
30 doi:10.1152/ajpheart.01251.2006

31 25. Medei E, Marocolo M, Rodrigues DC, Arantes PC, Takiya CM, Silvia J, Rondinelli E, Goldenberg RC, De
32 Carvalho AC, Nascimento JH (2010) Chronic treatment with anabolic steroids induces ventricular
33 repolarization disturbances: cellular, ionic and molecular mechanism. J Mol Cell Cardiol (49):165-175.
34 doi:10.1016/j.yjmcc.2010.04.014

35 26. Penna CA, G. Mancardi, D. Tullio, F. Piccione, F. Spaccamiglio, A. Racca, , S. Pagliaro P (2008) Synergistic
36 effects against post-ischemic cardiac dysfunction by sub-chronic nandrolone pretreatment and
37 postconditioning: role of beta2-adrenoceptor

38 . J Physiol Pharmacol 59 (4):645-659

39 27. Penna C, Tullio F, Perrelli MG, Moro F, Abbadessa G, Piccione F, Carriero V, Racca S, Pagliaro P (2011)
40 Ischemia/reperfusion injury is increased and cardioprotection by a postconditioning protocol is lost as
41 cardiac hypertrophy develops in nandrolone treated rats. Basic Res Cardiol 106:409-420.
42 doi:10.1007/s00395-010-0143-y

43

44 28. Şahin E, Gümüşlü S (2007) Immobilization stress in rat tissues: alterations in protein oxidation, lipid
45 peroxidation and antioxidant defense system. Comp Biochem Physiol Toxicol Pharmacol 144:342-347.
46 doi:org/10.1016/j.cbpc.2006.10.009

- 1 29. Atif F, Yousuf S, Agarwal SK (2008) Restraint stress-induced oxidative damage and its amelioration with
2 selenium. *Eur J Pharmacol* 600:59-63. doi:10.1016/j.ejphar.2008.09.029
- 3
- 4 30. Penna C, Abbadessa G, Mancardi D, Spaccamiglio A, Racca S, Pagliaro S (2007) Nandrolone-
5 pretreatment enhances cardiac beta(2)-adrenoceptor expression and reverses heart contractile down-
6 regulation in the post-stress period of acute stressed rats. *J Steroid Biochem Mol Biol* 107:106-113.
7 doi:org/10.1016/j.jsbmb.2007.05.005
- 8
- 9 31. Pope HG, Jr., Katz DL (1994) Psychiatric and medical effects of anabolic-androgenic steroid use. A
10 controlled study of 160 athletes. *Arch Gen Psychiatry* 51:375-382.
11 doi:10.1001/archpsyc.1994.03950050035004
- 12 32. Sweerts BW, Jarrott B, Lawrence AJ (1999) Expression of preprogalanin mRNA following acute and
13 chronic restraint stress in brains of normotensive and hypertensive rats. *Molecular Brain Research* 69:113-
14 123. doi:org/10.1016/S0169-328X(99)00095-9
- 15 33. Tsuchida M, Miura T, Mizutani K, Aibara K (1985) Fluorescent substances in mouse and human sera as a
16 parameter of in vivo lipid peroxidation. *Biochim Biophys Acta* 834:196-204
- 17 34. Bernheim F, Bernheim ML, Wilbur KM (1948) The reaction between thiobarbituric acid and the
18 oxidative products of certain lipid. *J Biol Chem* 174:257-264
- 19 35. Lowry OH, Rosebrough NJ, Farr AL, Randall RJ (1951) Protein measurement with Folin phenol reagent. *J*
20 *Biol Chem* 193:265-275
- 21 36. Liu G, Feinstein SI, Wang Y, Dodia C, Fisher D, Yu K, Ho YS, Fisher AB (2010) Comparison of glutathione
22 peroxidase 1 and peroxiredoxin 6 in protection against oxidative stress in the mouse lung. *Free Radic Biol*
23 *Med* 49 ((7)):1172-1181. doi:10.1016/j.freeradbiomed.2010.07.002
- 24
- 25 37. Xu F, Yu H, Liu J, Cheng (2013) α B-crystallin regulates oxidative stress-induced apoptosis in cardiac H9c2
26 cells via the PI3K/AKT pathway. *Mol Biol Rep*
- 27 40:2517-2526
- 28 38. Madrigal JL, Olivenza R, Moro MA, Lizasoain I, Lorenzo P, Rodrigo J, Leza JC (2001) Glutathione
29 depletion, lipid peroxidation and mitochondrial dysfunction are induced by chronic stress in rat brain.
30 *Neuropsychopharmacology* 24:420-429. doi:10.1016/S0893-133X(00)00208-6
- 31
- 32 39. Zafir A, Banu N (2009) Modulation of in vivo oxidative status by exogenous corticosterone and restraint
33 stress in rats. *Stress* 12 (2):167-177. doi:10.1080/10253890802234168
- 34 40. Marques-Neto S, Ferraz E, Rodrigues D, Njaine B, Rondinelli E, Campos de Carvalho A, Nascimento J
35 (2014) AT1 and aldosterone receptors blockade prevents the chronic effect of nandrolone on the exercise-
36 induced cardioprotection in perfused rat heart subjected to ischemia and reperfusion. *Cardiovasc Drugs*
37 *Ther* 28 (2):125-135. doi:10.1007/s10557-013-6503-8
- 38 41. Acharjee BK, Mahanta R, Borkotoky A (2010) Nandrolone decanoate enhances the activities of
39 cholanthrene induced glutathione-s-transferase in liver tissue of albino mice. *Drug Metab Lett* 4 (1-6)
- 40 42. Racca S, Piccione F, Spaccamiglio A, Carriero VM, De Francia S, Cangemi L, Esculapio P, Papotti M,
41 Migliaretti G, Portaleone P, Di Carlo F, Abbadessa G (2012) Effects of sub-chronic nandrolone
42 administration on hormonal adaptive response to acute stress in rats. *Psychoneuroendocrinology* 37:1234-
43 1247. doi:10.1016/j.psyneuen.2011.12.017
- 44
- 45 43. Iuchi T, Akaike M, Mitsui T, Ohshima Y, Shintani Y, Azuma H, Matsumoto T (2003) Glucocorticoid excess
46 induces superoxide production in vascular endothelial cells and elicits vascular endothelial dysfunction. *Circ*
47 *Res* 92:81-87. doi:10.1161/01.RES.0000050588.35034.3c

- 1 44. Sato H, Takahashi T, Sumitani K, Takatsu H, Urano S (2010) Glucocorticoid generates ROS to induce
2 oxidative injury in the hippocampus, leading to impairment of cognitive function of rats. *J Clin Biochem*
3 *Nutr* 47:224-232. doi:10.3164/jcbrn.10-58
- 4 45. Forman HJ, Maiorino M, Ursini F (2010) Signaling functions of reactive oxygen species. *Biochemistry*
5 49:835-842. doi:10.1021/bi9020378
- 6
- 7 46. Nagy N, Malik G, Fisher AB, Das DK (2006) Targeted disruption of peroxiredoxin 6 gene renders the
8 heart vulnerable to ischemia-reperfusion injury. *Am J Physiol Heart Circ Physiol* 291 ((6)):H2636-2640.
9 doi:10.1152/ajpheart.00399.2006
- 10 47. Rhee SG, Chae HZ, Kim K (2005) Peroxiredoxins: A historical overview and speculative preview of novel
11 mechanisms and emerging concepts in cell signalling. *Free Radic Biol Med* 38:1543-1552.
12 doi:org/10.1016/j.freeradbiomed.2005.02.026
- 13 48. Aggeli IK, Beis I, Gaitanaki C (2008) Oxidative stress and calpain inhibition induce alpha B-crystallin
14 phosphorylation via p38-MAPK and calcium signalling pathways in H9c2 cells. *Cell Signal* 20 (7):1292-1302.
15 doi:10.1016/j.cellsig.2008.02.019
- 16 49. Liu S, Li J, Tao Y, Xiao X (2007) Small heat shock protein alpha B-crystallin binds to p53
17 to sequester its translocation to mitochondria during hydrogen peroxide-induced apoptosis. *Biochem*
18 *Biophys Res Commun* 354:109-114. doi:10.1016/j.bbrc.2006.12.152
- 19
- 20 50. Shin JH, Kim SW, Lim CM, Jeong JY, Piao CS, Lee JK (2009) AlphaB-crystallin suppresses oxidative stress-
21 induced astrocyte apoptosis by inhibiting caspase-3 activation. *Neurosci Res* 64:355-361.
22 doi:10.1016/j.neures.2009.04.006
- 23
- 24 51. Ray PS, Martin JL, Swanson EA, Otani H, Dillmann WH, Das DK (2001) Transgene overexpression of
25 alphaB crystallin confers simultaneous protection against cardiomyocyte apoptosis and necrosis during
26 myocardial ischemia and reperfusion. *FASEB J* 15:393-402. doi:10.1096/fj.00-0199com
- 27 52. Morrison LE, Whittaker RJ, Klepper RE, Wawrousek EF, Glembotski CC (2004) Roles for alphaB-crystallin
28 and HSPB2 in protecting the myocardium from ischemia-reperfusion-induced damage in a KO mouse model
29 *Am J Physiol Heart Circ Physiol* 286:H847-H855. doi:10.1152/ajpheart.00715.2003
- 30 53. Golenhofen N, Redel A, Wawrousek EF, Drenckhahn D (2006) Ischemia-induced increase of stiffness of
31 alpha B-crystallin/HSPB2-deficient myocardium. *Pflugers Arch* 451:518-525. doi:10.1007/s00424-005-
32 1488-1
- 33 54. Mak S, Newton GE (2001) Vitamin C augments the inotropic response to dobutamine in humans with
34 normal left ventricular function. *Circulation* 103:826-830. doi:10.1161/01.CIR.103.6.826
- 35 55. Kubin AM, Skouma R, Tavi P, Kónyi A, Perjés A, Leskinen H, Ruskoaho H, Szokodi I (2011) Role of
36 reactive oxygen species in the regulation of cardiac contractility. *J Mol Cell Cardiol* 50:884-893.
37 doi:10.1016/j.yjmcc.2011.02.005

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1 **Fig. 1** Restraint stress increases plasma HNE and MDA adduct levels. The boxes indicate the lower
2 and upper quartiles, and the central line is the median. The dashed line represents the mean. The
3 whiskers above and below the boxes indicate a distance of 1.5 IQR. * $p < 0.05$.
4 HNE denotes 4-hydroxynoneal; MDA malondialdehyde; IQR interquartile range.

5
6 **Fig. 2** Free MDA levels in left heart ventricle are lowered by ND treatment upon restraint stress.
7 Box plot of MDA levels in left heart ventricular tissue (log(nmol/g)) in ND-treated and control
8 animals. The boxes indicate the lower and upper quartiles, and the central line is the median. The
9 dashed line represents the mean. The whiskers above and below the boxes indicate a distance of 1.5
10 IQR. Two-way ANOVA and post hoc Tukey test showed significant differences between ND and
11 ND+S ($p=0.027$), V and V+S ($p=0.002$), ND+S and V+S ($p=0.001$).
12 MDA denotes malondialdehyde; ND nandrolone decanoate; V vehicle-treated group; V+S vehicle-
13 treated group exposed to restraint stress; ND nandrolone-treated group; ND+S nandrolone-treated
14 group exposed to restraint stress; IQR interquartile range.

15
16 **Fig. 3** Increased GST protein levels in left heart ventricular tissue samples from ND-treated animals.
17 Representative Western blot image showing quantification of GST protein levels.

18 **Fig. 4** Measurement of blood LDH and CK-MB activity. Box plot of LDH (panel A) and CK-MB
19 isozyme (panel B) activity levels (U/L). The boxes indicate the lower and upper quartiles. The
20 central and the dashed lines represent the median and the mean values, respectively. The whiskers
21 above and below the boxes indicate a distance of 1.5 IQR. Two-way ANOVA and post hoc Tukey
22 test showed significant differences between the V+S vs ND groups and the V+S vs ND+S

23 groups.**Fig. 5** Two-dimensional gel electrophoresis (2-DE) displaying different patterns in the
24 lysates obtained from left heart ventricular tissue samples from the two groups exposed to restraint
25 stress (V+S and ND+S). Proteins from V+S (panel A) and ND+S (panel B) left heart ventricular
26 tissues were separated by isoelectric focusing on 7-cm strips with a non linear 3 to 10 pH gradient
27 and subjected to SDS-polyacrylamide gel electrophoresis. Gels were stained with Coomassie Blue
28 (G250). The numbers indicate the spots analyzed by mass spectrometry. Molecular size markers are
29 indicated on the left.

30
31 **Fig. 6** Immunoblots of PRDX6 and CRYAB proteins in left heart ventricular tissue. Histograms
32 show the relative concentrations of the proteins normalized to the house-keeping protein tubulin
33 (TUB).

1 PRDX6 denotes peroxiredoxin 6; CRYAB alpha B-crystallin; V vehicle-treated group; V+S
2 vehicle-treated group exposed to restraint stress; ND nandrolone-treated group; ND+S nandrolone-
3 treated group exposed to restraint stress. Two-way ANOVA and post hoc Tukey test showed
4 significant differences between the groups. PRDX6 * $p < 0.05$ vs V and V+S, $n=3$; CRYAB * $p < 0.05$
5 vs V; # $p < 0.05$ vs V+S, $n=3$.
6 The immunoblots are from one representative experiment.

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