RETRACTED: Testosterone Protects Mitochondrial Function and Regulates Neuroglobin Expression in Astrocytic Cells Exposed to Glucose Deprivation

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Testosterone is a hormone that has been shown to confer neuroprotection from different insults affecting the central nervous system (CNS). Testosterone induces this protection by different mechanisms that include the activation of anti-apoptotic pathways that are directly implicated in neuronal survival. However, little attention has been devoted to its actions on glial cells. In the present study, we have assessed whether testosterone exerts protection in a human astrocyte cell model, the T98G cells. Our results indicate that testosterone improves cell survival and mitochondrial membrane potential and reduces nuclear fragmentation and reactive oxygen species (ROS) generation. These effects were accompanied by a positive regulation of neuroglobin, an oxygen-binding and sensor protein, which may serve as a regulator of ROS and nitrogen reactive species (NOS), and these protective effects of testosterone may be at least in part mediated by estradiol and DHT. In conclusion, these findings suggest that astroglia may mediate some of the protective actions of testosterone in the brain upon pathological conditions.

Keywords: testosterone, mitochondria, brain, glucose deprivation, neuroglobin, neuroprotection

INTRODUCTION

Testosterone, a gonadal hormone, modulates aggressive and sexual behavior (Christiansen, 2001), has anxiolytic and antidepressant-like effects (Carrier et al., 2015), affects cognition (Cherrier, 2005), and regulates synaptic plasticity in the brain (Hatanaka et al., 2015). Moreover, testosterone has been shown to prevent neuronal cell death, to improve memory after damage (Fanaei et al., 2014), and to regulate the activation and reactivity of glial cells upon brain injury (Barreto et al., 2007). The neuroprotective actions of testosterone may in part explain that the decrease in its plasma levels with aging is associated with an increase in neurodegenerative diseases (Bialek et al., 2004; Gold and Voskuhl, 2006; Rosario et al., 2011; Barron and Pike, 2012; Khasnavis et al., 2013). Furthermore, testosterone may be converted into estradiol by aromatase, or dihydrotestosterone (DHT) via 5α-reductase, and part of the protective effects of testosterone might be due to its metabolites (Barreto et al., 2007).

Improvement of mitochondrial function may be one of the mechanisms involved in the protective actions of testosterone in the brain. For example, testosterone enhances the functional recovery in animals subjected to cerebral ischemia by promoting the increase of BDNF, antioxidant

defense/activity and neurogenesis (Chisu et al., 2006; Fanaei et al., 2014). Similarly, chronic treatment with testosterone modulated the Nrf2-Are activation (Zhang et al., 2013), improved behavior in aged rats (Zhang et al., 2013), and decreased oxidative stress and cell damage induced by 3-nitropropionic acid in ovariectomized rats (Tunez et al., 2007). Accordingly, testosterone suppression is associated to high brain susceptibility to oxidative damage (Son et al., 2016), accelerated neuronal death (Ota et al., 2012), augmented malondiadehyde (MDA) levels, increased Bax immunoreactivity, and decreased expression of mitochondrial enzymes (Meydan et al., 2010). This decrease is accompanied by a downregulation of mitochondrial gene expression and decline in PGC-1α (Hioki et al., 2014). More recently, it has been reported that neuroglobin (Ngb) is involved in the protective actions of estradiol and might be implicated in the anti-inflammatory and neuroprotective properties of this hormone in astrocytes and neurons (De Marinis et al., 2010, 2013a,b). However, it is unknown whether testosterone might exert its effects through modulation of Ngb in astrocytes upon metabolic damage.

MATERIALS AND METHODS

T98G Cell Culture

T98G cell line was used as an astrocytic cell model system (ATCC CRL-1690) (Gasque et al., 1996; de Joannon et al., 2000; Mao et al., 2006). Cells were maintained under exponential growth in Dulbecco's modified Eagle's medium (DMEM) (LONZA, Walkersville, USA), containing 10% fetal bovine serum (FBS) (LONZA, Walkersville, USA), and 10U penicillin/10 μg streptomycin/25 ng amphotericin (LONZA, Walkersville, USA). The medium was changed three times a week. Cultures were incubated at 37°C in a humidified atmosphere containing 5% carbon dioxide and 95% oxygen. Cells were seeded in 96-well plates for cell death measurement, 12-well plates for flow cytometry determinations and 24-well plate for tetra-methyl rhodamine methyl ester (TMRM) and immunofluorescence measurements.

Drug Treatments

Once the cells were seeded in the multi-well plates, the cultured media was replaced with DMEM supplemented with 1% fetal bovine serum for 12 h (LONZA, Walkersville, USA). Twenty-four hours before glucose deprivation some cell cultures were incubated in DMEM serum-free medium containing 1, 10, or 100 nM testosterone, 10 nM estradiol or 10 nM DHT. Testosterone was dissolved in 0.01%, DMSO as stock solution at 5 μM, while estradiol and DHT were dissolved in 0.0001% ethanol and 0.0001% methanol, respectively, and further dilutions were made using serum-free culture medium.

Glucose Deprivation

Glucose deprivation was performed as previously reported (Avila Rodriguez et al., 2014). Briefly, before glucose deprivation, cells were washed three times with glucose-free, balanced salt solution (BSS 0) containing in mM: NaCl, 116; CaCl$_2$, 1.8; MgSO$_4$, (7.H2O) 0.8; KCl, 5.4; NaH$_2$PO4, 1; NaHCO$_3$, 14.7, and 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid (HEPES), 10; pH 7.4. Subsequently, cells were incubated with BSS0 and transferred

to the incubator for 24 h. The wash controls cells had their medium changed to BSS5, which was identical to BSS0, but supplemented with 5.5 mM glucose.

Determination of Viability and Nuclear Fragmentation

Cells were seeded into 96-wells plates in DMEM culture medium containing 10% FBS at seeding density of 10,000 cells per well and incubated for 2–3 days until they reach confluence. Subsequently, cells were treated according to different experimental paradigms. Viability was determined by propidium iodide (PI) assay and assessed by flow cytometry. Briefly, cells were seeded into 24-wells plates in DMEM culture medium containing 10% bovine fetal serum at seeding density of 30,000 cells per well, incubated for 2–3 days until they reach confluence. Then, cells were subjected to drug and injury conditions. Once the treatments were finished, cells were washed in PBS and detached with trypsin (Trypsin/EDTA 500 mg/L:200 mg/L; LONZA, Walkersville, USA). Then, cells were stained with PI dissolved in PBS at a final concentration of 10 μg/ml for 10 min. Subsequently cells were analyzed in a Guava EasyCyte™ (Millipore, Billerica, Massachusetts, USA) cytometer. Each assay was performed with a minimum of six replicates for each condition. The experiment was repeated 3 times.

Nuclear fragmentation was determined by Hoechst 33258 staining. After exposure to glucose deprivation and different experimental paradigms, cells were washed three times in phosphate-buffered saline and fixed for 20 min in 4% formaldehyde at room temperature. Subsequently, cells were washed and labeled with Hoechst 33258 (5 mg/ml; Invitrogen) for 15 min. Cell nuclei were observed and photographed using an inverted fluorescence microscope Olympus IX-53. The number of fragmented nuclei was determined in at least eight randomly selected areas (0.03 mm^2) within series of wells from each experimental group. The experiment was repeated 3 times. Data were expressed as a percentage of nuclear fragmented cells relative to the value in control cultures.

Determination of Reactive Oxygen Species (ROS)

Reactive oxygen species levels were evaluated by flow cytometry as previously described (Avila Rodriguez et al., 2014). Briefly, cells were seeded at a density of 75,000 per well into 12-well plates in DMEM culture medium containing 10% FBS and then were treated according to each experimental paradigm in the next day. To measure the effect of testosterone on superoxide (O^{2-}) or peroxide hydrogen levels (H$_2$O$_2$), cells were treated in the dark for 30 min at 37°C with 10 mM dihydroethidium (DHE; Sigma) or 10 μmol/L 2′,7′-dichlorofluorescin diacetate (DCFDA) staining, respectively. Then, cells were washed in PBS and detached with trypsin solution (Trypsin/EDTA 500 mg/L:200 mg/L; LONZA, Walkersville, USA) for flow cytometry analysis. Cells were analyzed in a Guava EasyCyte™ (Millipore, Billerica, Massachusetts, USA) cytometer. Each assay was performed with a minimum of six replicates for each condition. The experiment was repeated 3 times.

Determination of Mitochondrial Membrane Potential

Mitochondrial membrane potential was evaluated using Tetramethyl Rhodamine Methyl Ester (TMRM) and assessed by flow cytometry and qualitative images were assessed using fluorescence microscope. For flow cytometry analysis, cells were seeded at a density of 75,000 cells per well into 12-well plates and treated according to each experimental paradigm in the next day. After glucose deprivation for 24 h, cells were loaded in the dark with 500 nM TMRM at 37°C for 20 min. Thereafter, cells were washed with PBS to eliminate all the non-sequestered dye, and detached using trypsin. Then the cells were analyzed by flow cytometry. As experimental control, we used the uncoupler CCCP (Sigma-Aldrich V0627; 100 nM) to dissipate the membrane potential and define the baseline for analysis of mitochondrial potential. Each assay was performed with a minimum of six replicates for each condition. Each experiment was repeated at least 3 times.

For TMRM fluorescence imaging, cells were seeded at a density of 30,000 cells per well into 24-well plates in DMEM culture medium containing 10% FBS, and subjected to each experimental paradigm in the next day. Once finished the treatments, cells were subjected to glucose deprivation and then incubated with TMRM for 30 min. Finally, cells were washed with PBS and photographed in an Olympus IX-53 fluorescence microscope.

Determination of Mitochondrial Mass

Mitochondrial mass was evaluated using Nonyl acridine orange (NAO). NAO is a cell-permeate, cationic fluorescent dye sequestered by active mitochondria. After 24 h of treatments, cells were loaded in the dark with 5 μM NAO at 37°C for 20 min. Thereafter, cells were washed with PBS to eliminate all non-sequestered dye. Mitochondrial mass was further evaluated by flow cytometry in a GuavaR EasyCyte™ (Millipore) cytometer.

Estimation of Cellular Mean Fluorescence Intensity

The analysis of cellular fluorescence for was performed using ImageJ version 1.47v (Hartig, 2013). The microphotographs were loaded and background signals were eliminated from the images. Subsequently, 20 cells were randomly selected using a numbered grid in each microphotograph. The mean fluorescence value of the 20 cells was determined in eight microphotographs for each treatment using the Measure algorithm of ImageJ and selecting each cell manually via ROI's (Regions of Interest) Management. Cells were analyzed in an area of $0.03 \, mm^2$. There were no variations in the conditions of the image processing. Each assay was performed with a minimum of six replicate wells for each condition and experiments were repeated three times.

Neuroglobin Assessment

Ngb1 was assessed by immunofluorescence following the experimental treatments previously described. For neuroglobin immunofluorescence, cells were cultured on 24-wells plates, and at the end of treatments, cells were washed in PBS and fixed with 4% paraformaldehyde for 20 min at room temperature.

Subsequently, cells were treated for 3 min in 0.1% Triton X-100 in tris buffer saline (TBS) with 2% BSA. After, this permeabilization step, cells were washed with PBS, blocked with 2% BSA and incubated overnight at 4°C with mouse anti-Ngb1 antibody (Abcam® ab37258; diluted 1:50). Then, cells were washed three times for 5 min with TBS and incubated for 45 min at room temperature with Dylight conjugated-488 anti-mouse secondary antibody, diluted 1:1000. Cells were then washed three times, and photographed in a fluorescence Olympus IX-53 inverted microscope.

Statistical Analysis

Data obtained was tested for normal distribution by Kolmogorov–Smirnov test and homogeneity of variance by Levene's test. Then, data were examined by analysis of variance, followed by Dunnet's *post hoc* test for comparisons between controls and treatments and Tukey's *post hoc* test for multiple comparisons between the means of treatments and timepoints. Data are presented as mean ± SEM. A statistically significant difference was defined at $p < 0.05$.
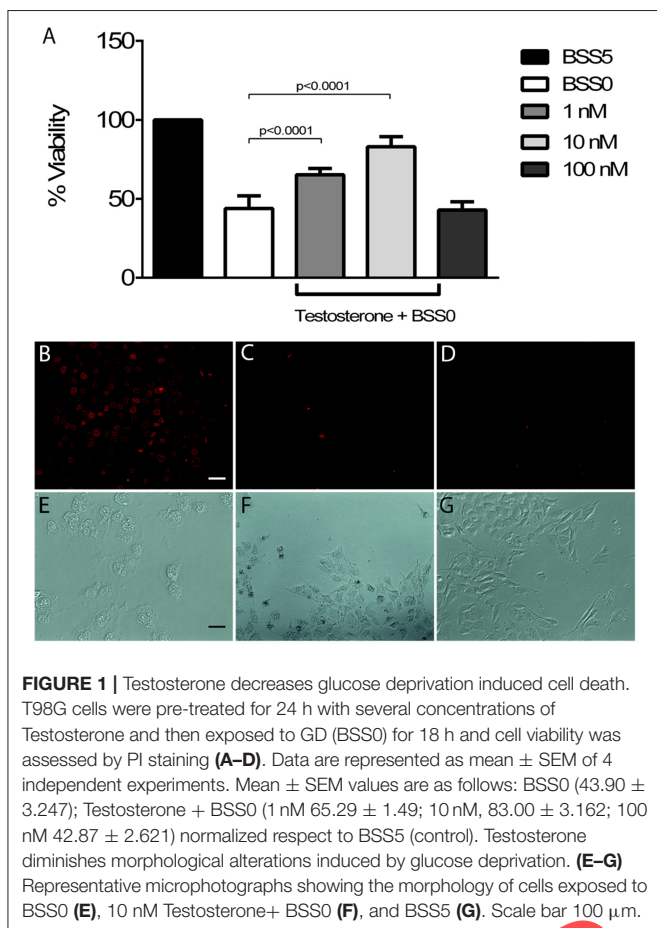
RESULTS

Testosterone Increased Cell Viability and Preserved Morphology in Glucose Deprived Cells

Initially, optimal experimental conditions of testosterone treatment upon glucose deprivation (GD) were assessed. Cells were pretreated with testosterone at different concentrations for 24 h and subsequently subjected to GD for 18 h. Cells pretreated with 1, 10, and 100 nM testosterone showed a 65.29% ($p < 0.0001$), 83.00% ($p < 0.0001$), and 42.87% increase in cell viability by PI assay when compared to BSS0 cells, respectively, (**Figure 1A**). Qualitative analysis for PI fluorescence confirmed the results (**Figures 1B–D**). Based on these results, the 10 nM dose of testosterone was used in further experiments.

Cell viability and morphology are tightly related, and increases in oxidative stress usually induce noticeable morphological changes. In agreement with the observed changes in cell viability, GD cells showed smaller cell bodies and less cellular processes than control cells (**Figure 1E**). Testosterone (10 nM) preserved cell morphology even in cells treated with medium without glucose (BSS0, **Figure 1F**).

Testosterone Prevented Nuclear Fragmentation and Chromatin Condensation in GD Cells

To further assess the protective effect of testosterone, we studied its effect on nuclear fragmentation and nuclear condensation in GD cells using Hoescht 33258 staining. **Figure 2** shows that GD for 18 h increased nuclear fragmentation and chromatin condensation by 48.50% in T98G cells when compared to control (BSS5, **Figure 2**, $p < 0.0001$). GD dramatically induced nuclear fragmentation and chromatin condensation, which was markedly reduced to 4.73% in the presence of testosterone ($p < 0.0001$).

FIGURE 1 | Testosterone decreases glucose deprivation induced cell death. T98G cells were pre-treated for 24 h with several concentrations of Testosterone and then exposed to GD (BSS0) for 18 h and cell viability was assessed by PI staining **(A–D)**. Data are represented as mean ± SEM of 4 independent experiments. Mean ± SEM values are as follows: BSS0 (43.90 ± 3.247); Testosterone + BSS0 (1 nM 65.29 ± 1.49; 10 nM, 83.00 ± 3.162; 100 nM 42.87 ± 2.621) normalized respect to BSS5 (control). Testosterone diminishes morphological alterations induced by glucose deprivation. **(E–G)** Representative microphotographs showing the morphology of cells exposed to BSS0 **(E)**, 10 nM Testosterone+ BSS0 **(F)**, and BSS5 **(G)**. Scale bar 100 μm.

FIGURE 2 | Testosterone reduces nuclear fragmentation following glucose deprivation. The panel shows representative microphotographs of T98G cells exposed to BSS0 **(A)**, BSS5 **(B)**, and Testosterone + BSS0 **(C)**. Scale bar 100 μm. The bar graph shows the percentage of cells with fragmented nuclei. Data are represented as mean ± SEM of 3 independent experiments. Mean ± SEM values are as follows: BSS5 (1.193 ± 0.7062); BSS0 (48.50 ± 2.929), Testosterone + BSS0 (4.30 ± 2.439).

Testosterone Protected Mitochondria by Reducing Reactive Oxygen Species Production and Improving Mitochondrial Membrane Potential and Mass

Glucose deprivation induces the generation of ROS, especially superoxide anions and hydrogen peroxide. Our results show that GD augmented O_2-production, and that testosterone significantly reduced superoxide generation (**Figures 3A–C**, $p < 0.0004$). A similar effect of testosterone in reducing hydrogen peroxide (H_2O_2) production was also observed. **Figure 3D** shows that H_2O_2 levels increased in the early hours after the insult, reaching the highest level after 6 h and decreasing thereafter. Fluorescence levels of H_2O_2 were 396, 244, 166, and 138 at 6, 9, 12, and 18 h, respectively. Testosterone significantly attenuated H_2O_2 levels at 6 h ($p < 0.0368$), 9 h ($p < 0.0047$), 12 h ($p < 0.0319$), and 18 h ($p < 0.0484$) in comparison to cells treated with BSS0 alone (**Figure 3D**).

The mitochondrial membrane potential ($\Delta\psi m$) was assessed using TMRM staining by flow cytometry. **Figure 4** shows differences in $\Delta\psi m$ in cells exposed to BSS0 (**Figure 4A**), BSS5 (**Figure 4B**), and Testosterone + BSS0 (**Figure 4C**). Cells pre-treated with testosterone maintained mitochondrial membrane potential similar to that of BSS5 levels. To observe the kinetics of membrane potential in
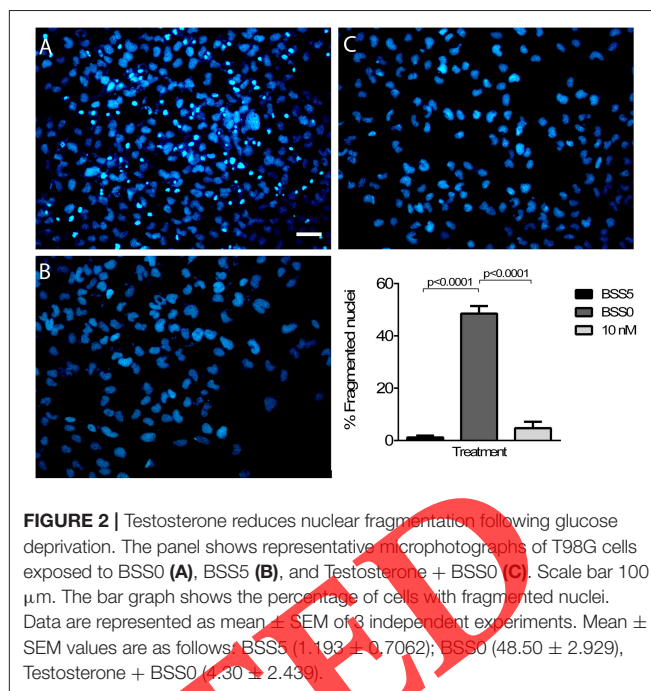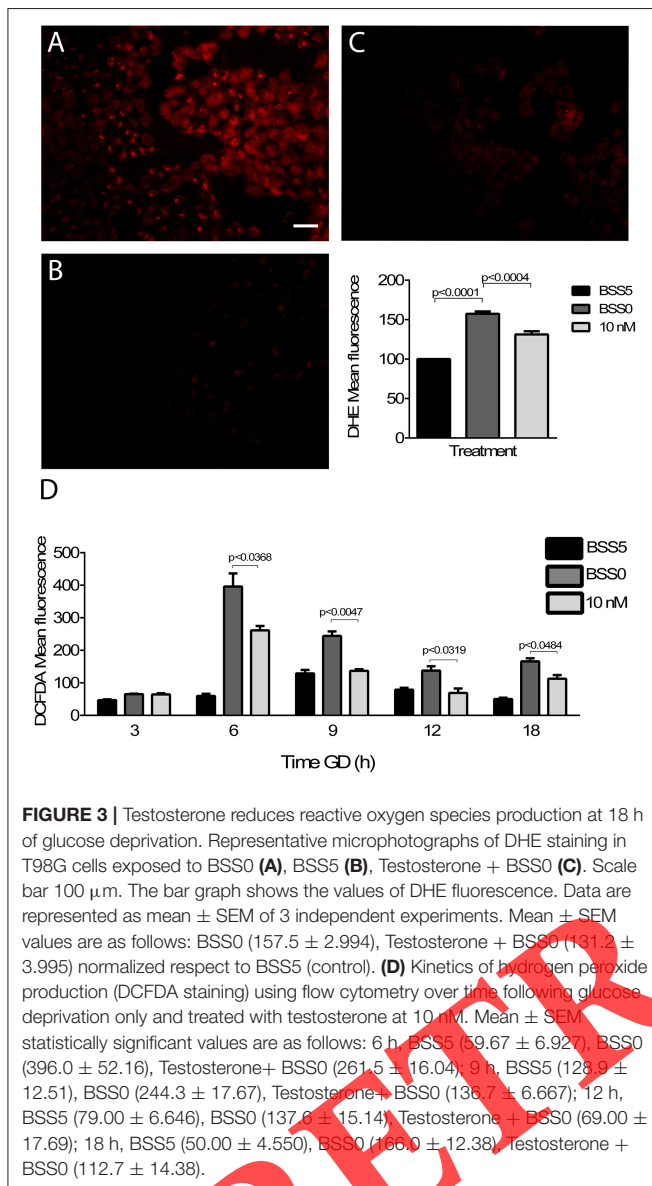
different time points, the analysis was performed at 3, 6, 9, 12, and 18 h after GD. The mitochondrial membrane potential was preserved during the first 3 h of GD with no significant changes. However, significant loss of $\Delta\psi m$ was observed at 12 ($p < 0.0004$) and 18 h ($p < 0.0003$) compared to BSS5. However, testosterone preserved mitochondrial membrane potential at 12 ($p < 0.0012$) and 18 h ($p < 0.0059$; **Figure 4D**).

Similar results were observed when staining cells for NAO (nonyl acridine orange) to assess mitochondrial mass. Qualitative results suggested that GD may induce a loss of mitochondrial mass (**Figure 5A**) and that testosterone reduced this effect (**Figure 5C**). Quantitative studies using flow cytometry for NAO confirmed these observations. GD significantly reduced mitochondrial mass ($p < 0.0009$) in comparison to BSS5, and testosterone significantly increased NAO fluorescence in GD cells ($p < 0.0306$).

Testosterone Increases Neuroglobin Expression in GD Cells

Neuroglobin is a protein suspected to play an important role in detoxifying ROS and neuroprotection against different types of insults (De Marinis et al., 2010, 2013a,b). Because of its potential importance for cell survival after GD, neuroglobin immunoreactivity was assessed by immunocytochemistry. The results showed that GD significantly induced the expression of neuroglobin (**Figure 6A**) that was significantly different from that of control values (BSS5, **Figure 6B**, $p < 0.0001$). Interestingly, testosterone was able to induce neuroglobin expression in GD cells when compared to GD only ($p < 0.0001$; **Figure 6C**).

FIGURE 3 | Testosterone reduces reactive oxygen species production at 18 h of glucose deprivation. Representative microphotographs of DHE staining in T98G cells exposed to BSS0 **(A)**, BSS5 **(B)**, Testosterone + BSS0 **(C)**. Scale bar 100 μm. The bar graph shows the values of DHE fluorescence. Data are represented as mean ± SEM of 3 independent experiments. Mean ± SEM values are as follows: BSS0 (157.5 ± 2.994), Testosterone + BSS0 (131.2 ± 3.995) normalized respect to BSS5 (control). **(D)** Kinetics of hydrogen peroxide production (DCFDA staining) using flow cytometry over time following glucose deprivation only and treated with testosterone at 10 nM. Mean ± SEM statistically significant values are as follows: 6 h, BSS5 (59.67 ± 6.927), BSS0 (396.0 ± 52.16), Testosterone+ BSS0 (261.5 ± 16.04); 9 h, BSS5 (128.9 ± 12.51), BSS0 (244.3 ± 17.67), Testosterone+ BSS0 (136.7 ± 6.667); 12 h, BSS5 (79.00 ± 6.646), BSS0 (137.6 ± 15.14), Testosterone + BSS0 (69.00 ± 17.69); 18 h, BSS5 (50.00 ± 4.550), BSS0 (166.0 ± 12.38), Testosterone + BSS0 (112.7 ± 14.38).
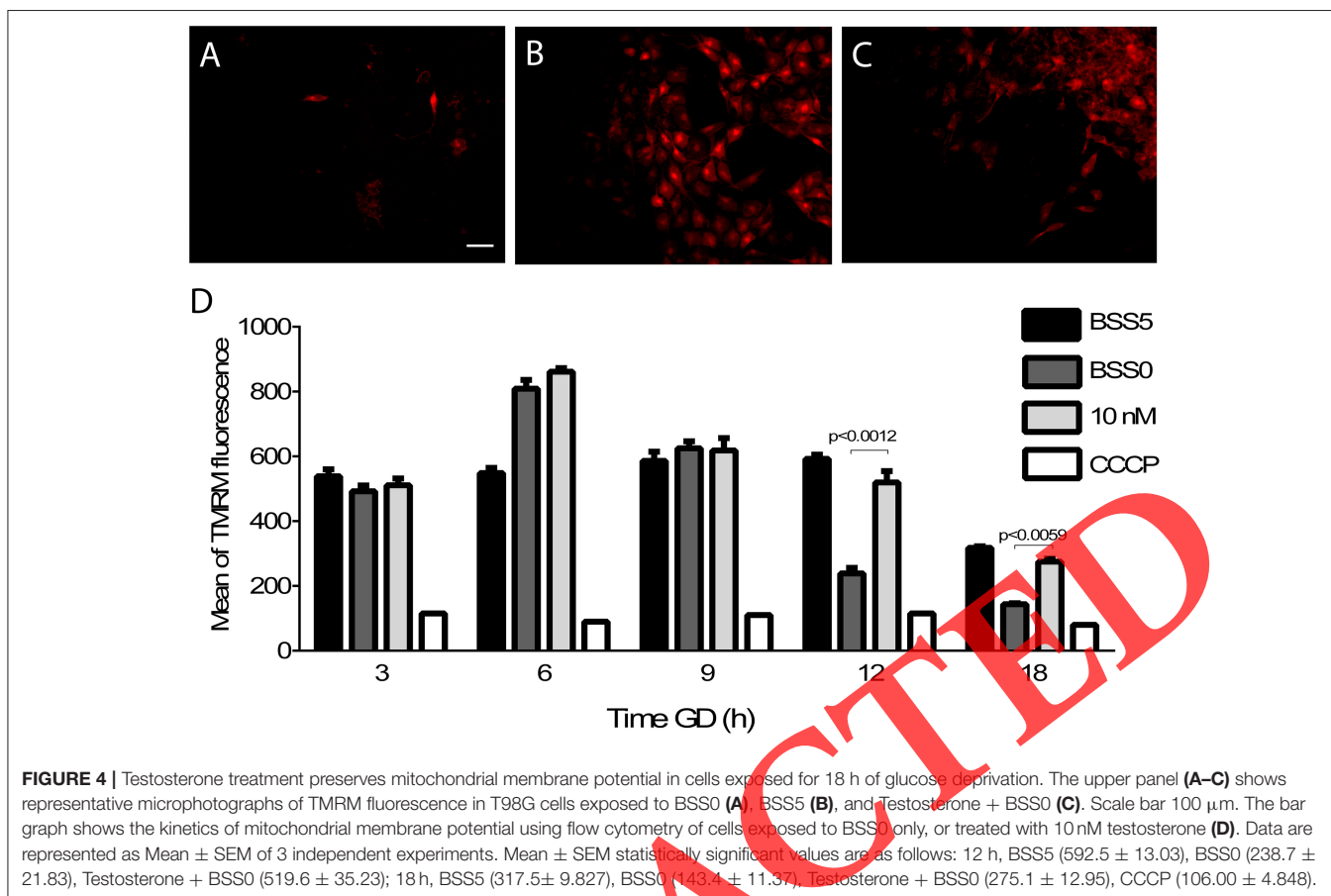
Estradiol and DHT Protect Mitochondria in Glucose-Deprived Cells

To determine whether testosterone might exert neuroprotective effects through its metabolites, cells were pre-treated with either 10 nM estradiol or 10 nM DHT before GD insult. Our results indicated that estradiol improved cell viability (**Figure 7A**, $p < 0.0001$) and mitochondrial membrane potential ($p < 0.0001$), reduced O_2-production (**Figure 7C**, $p < 0.0002$), and H_2O_2 levels (**Figure 7D**, $p < 0.0164$) and significantly increased mitochondrial mass (**Figure 7E**, $p < 0.0011$) in comparison to BSS0. Similarly, DHT was able to ameliorate cell survival ($p < 0.0001$) and mitochondrial membrane potential ($p = 0.0016$), diminished ROS levels ($p < 0.0001$ for both DHE and DCFDA levels), and augmented NAO fluorescence ($p < 0.0005$).

DISCUSSION

Previous evidence indicated that astrocytes play an important role in maintaining neuronal homeostasis and that astrocytic malfunctioning can severely impair neuronal metabolism and survival (Cabezas et al., 2012, 2014, 2016; Posada-Duque et al., 2014; Romero et al., 2014; Torrente et al., 2014). Therefore, it is thought that protecting astrocytes function might be a promissory strategy to promote neuronal survival following various brain insults. In this study, we addressed whether testosterone, an androgen with potent actions in the brain, may protect mitochondria from astrocytes exposed to glucose deprivation. Our results showed that testosterone increased cell survival and reduced nuclear fragmentation and chromatin condensation. These effects were accompanied by preservation of mitochondrial function and an augmented expression of neuroglobin.
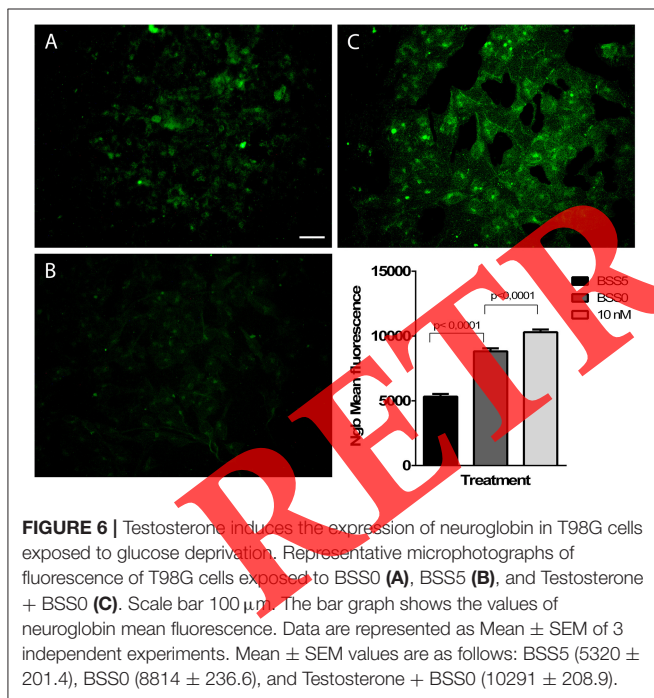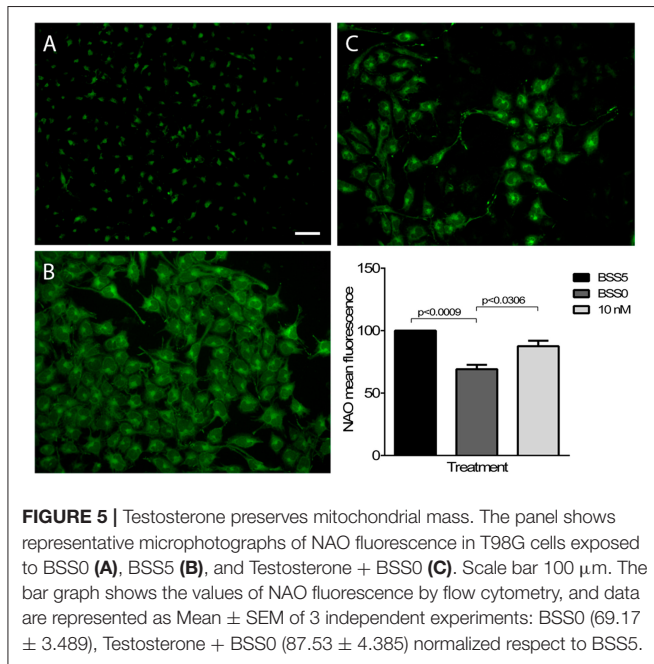
Testosterone can induce different metabolic and genomic responses in the brain. For example, it has been shown that testosterone and its main metabolite, dihydrotestosterone, reduced tissue damage and improved the outcome in an *in vivo* model of focal ischemia (Cheng et al., 2009; Uchida et al., 2009). Similarly, subcutaneous injection of testosterone (1 mg/kg) reduced astrogliosis and microgliosis following a stab wound injury in the brain (Barreto et al., 2007). The neuroprotective mechanism is highly dependent on the dose and a dosage to reach a more physiological concentration (10 nM), exerts neuroprotective effects whereas a 10 times higher dose of testosterone (100 nM) was not neuroprotective (Orlando et al., 2007). This data is consistent with the findings in the present study, where a pre-treatment with 10 nM testosterone improved cell survival (**Figure 1**), assessed as a decrease in PI staining (**Figure 1**). This effect can be mediated by different mechanisms. For example, Gurer et al. (2015) showed that testosterone reduced cell death by decreasing the activity of caspase-3, a protease and main effector of different apoptotic cascades. Also, Nguyen et al. (2005) showed that 10 nM testosterone increased the expression of protein kinases ERK1/2, and Rsk-1, and inactivated pro-apoptotic proteins such as Bad. In addition, testosterone can protect cells by improving mitochondrial functions. For example, although there are some conditions where ROS can be produced at low $\Delta\psi m$, pathophysiological levels of ROS are generally produced upon high levels of mitochondrial membrane potential. It has been shown that wherein $\Delta\psi m$ exceeds 140 mV (hyperpolarized membrane), there is an exponential increase in ROS generation in both mitochondrial complexes I and III (Liu, 1999). This data is in agreement with the results presented in this study, in which an exponential increase in H_2O_2 production was observed after 6 h of GD, a time point in which the mitochondrial membrane potential of cells T98G exposed to injury increased by 64.2% in comparison to the levels found after 3 h of GD. One explanation for this phenomenon is that cells may adapt their mitochondria membrane potential according to the cellular energy demands, regardless of whether this change may be potentially deleterious for cell survival. Another interpretation is that cells are experiencing apoptotic processes, specifically

FIGURE 4 | Testosterone treatment preserves mitochondrial membrane potential in cells exposed for 18 h of glucose deprivation. The upper panel **(A–C)** shows representative microphotographs of TMRM fluorescence in T98G cells exposed to BSS0 **(A)**, BSS5 **(B)**, and Testosterone + BSS0 **(C)**. Scale bar 100 μm. The bar graph shows the kinetics of mitochondrial membrane potential using flow cytometry of cells exposed to BSS0 only, or treated with 10 nM testosterone **(D)**. Data are represented as Mean ± SEM of 3 independent experiments. Mean ± SEM statistically significant values are as follows: 12 h, BSS5 (592.5 ± 13.03), BSS0 (238.7 ± 21.83), Testosterone + BSS0 (519.6 ± 35.23); 18 h, BSS5 (317.5± 9.827), BSS0 (143.4 ± 11.37), Testosterone + BSS0 (275.1 ± 12.95), CCCP (106.00 ± 4.848).

mitochondrial damage, which is characterized by excessive release of calcium, hyperpolarization of $\Delta\psi$m, and an explosive increase in the production of ROS (Kadenbach et al., 2004). Although H_2O_2 is relatively less reactive, it can form different hydroxy-reactive moieties in the presence of iron ions, which can initiate cascades of oxidative stress such as lipid peroxidation in the cell membrane. This oxidative stress is a key factor in neurodegenerative diseases and one of its main causes (Brand et al., 2004). Meanwhile, testosterone has shown to have the ability to mitigate these oxidative stress processes by reducing the levels of ROS, during injury caused by superoxide (Tunez et al., 2007; Meydan et al., 2010; Gurer et al., 2015; Xiao et al., 2015). This effect is consistent with the results obtained, indicating that testosterone can reduce superoxide levels in cells exposed to GD, possibly by mechanisms such us the stimulation of the activity of the superoxide dismutase (SOD; Li et al., 2006). Furthermore, it has been shown that testosterone has the ability to reduce the levels of hydrogen peroxide produced by GD in T98G cells. There is a clear relationship of ROS production with $\Delta\psi$m. For example, after an increase of $\Delta\psi$m, an increase in ROS production was observed. Nevertheless, this increase in ROS, and membrane hyperpolarization is not maintained over time during the insult, likely because cellular energy levels significantly decrease, given that cells exhaust its energy sources (glycogen and fatty acids

oxidation for example) for the production of ATP in the early hours of the insult (Korenic et al., 2014). Likewise, it is also possible that testosterone may inhibit mitochondria-mediated apoptosis (Tunez et al., 2007; Vasconsuelo et al., 2011; Gurer et al., 2015), since it has been shown that this hormone induced the expression of the anti-apoptotic protein Bcl-2 and reduced the pro-apoptotic protein Bax, in the cortex and hippocampus of neonatal rats following ischemic damage (Li et al., 2006).

Interestingly, we found that testosterone modulates the expression of neuroglobin, a hemoprotein that is widely expressed in neurons and in reactive astrocytes and reactive microglia upon injury (DellaValle et al., 2010; Li et al., 2014). Previous studies revealed that neuroglobin binds to O_2, is induced by hypoxia, and protects cell against death caused by ischemia or hypoxia (Sun et al., 2001, 2003). Also, neuroglobin improved mitochondrial permeability transition in OGD (oxygen glucose deprivation) primary cortical neurons (Yu et al., 2013a). The role of neuroglobin has been assessed in different insults, in which one of these studies showed that neuroglobin blockade worsened infarct volume and increased ROS (Sun et al., 2003). This decrease in neuroglobin has been also associated with an increased risk of developing Alzheimer disease in humans (Szymanski et al., 2010). Among the functions played by neuroglobin, it has been postulated

FIGURE 5 | Testosterone preserves mitochondrial mass. The panel shows representative microphotographs of NAO fluorescence in T98G cells exposed to BSS0 **(A)**, BSS5 **(B)**, and Testosterone + BSS0 **(C)**. Scale bar 100 μm. The bar graph shows the values of NAO fluorescence by flow cytometry, and data are represented as Mean ± SEM of 3 independent experiments: BSS0 (69.17 ± 3.489), Testosterone + BSS0 (87.53 ± 4.385) normalized respect to BSS5.

FIGURE 6 | Testosterone induces the expression of neuroglobin in T98G cells exposed to glucose deprivation. Representative microphotographs of fluorescence of T98G cells exposed to BSS0 **(A)**, BSS5 **(B)**, and Testosterone + BSS0 **(C)**. Scale bar 100 μm. The bar graph shows the values of neuroglobin mean fluorescence. Data are represented as Mean ± SEM of 3 independent experiments. Mean ± SEM values are as follows: BSS5 (5320 ± 201.4), BSS0 (8814 ± 236.6), and Testosterone + BSS0 (10291 ± 208.9).

FIGURE 7 | Estradiol (Est) and DHT protect mitochondria in GD cells. Estradiol and DHT, both metabolites of testosterone, were able to improve **(A)** cell viability [87.95 ± 2.87 for Est and 76.07 ± 4.27 vs. BSS0 (57.08 ± 3.08)] and **(B)** mitochondrial membrane potential [91.73 ± 6.09 for Est and 58.67 ± 3.68 for DHT vs. BSS0 (41.79 ± 5.10)], reduced **(C)** DHE fluorescence [175.6 ± 9.0 for Est and 139.4 ± 5.10 for DHT vs. BSS0 (194.45 ± 4.37)] and **(D)** H_2O_2 levels [59.83 ± 6.01 for Est and 42.27 ± 5.39 dor DHT vs. BSS0 (77.61 ± 5.0)]. Additionally, estradiol and DHT also augmented **(E)** mitochondrial mass [76.65 ± 2.94 for Est and 88.27 ± 3.57 for DHT vs. BSS0 (71.29 ± 3.12)], suggesting that testosterone protective effects on mitochondria might be in part mediated by its metabolites.

that this protein might help O_2 transport, and may serve as a sensor to hypoxia (Sun et al., 2003). Our findings demonstrate a significant increased neuroglobin expression in cells exposed to GD, which is consistent with the induction of this protein when cells are exposed to different insults. Similarly, it is observed that testosterone has an effect on the induction of neuroglobin by increasing its expression when compared to levels of that from BSS0. This behavior suggests that testosterone
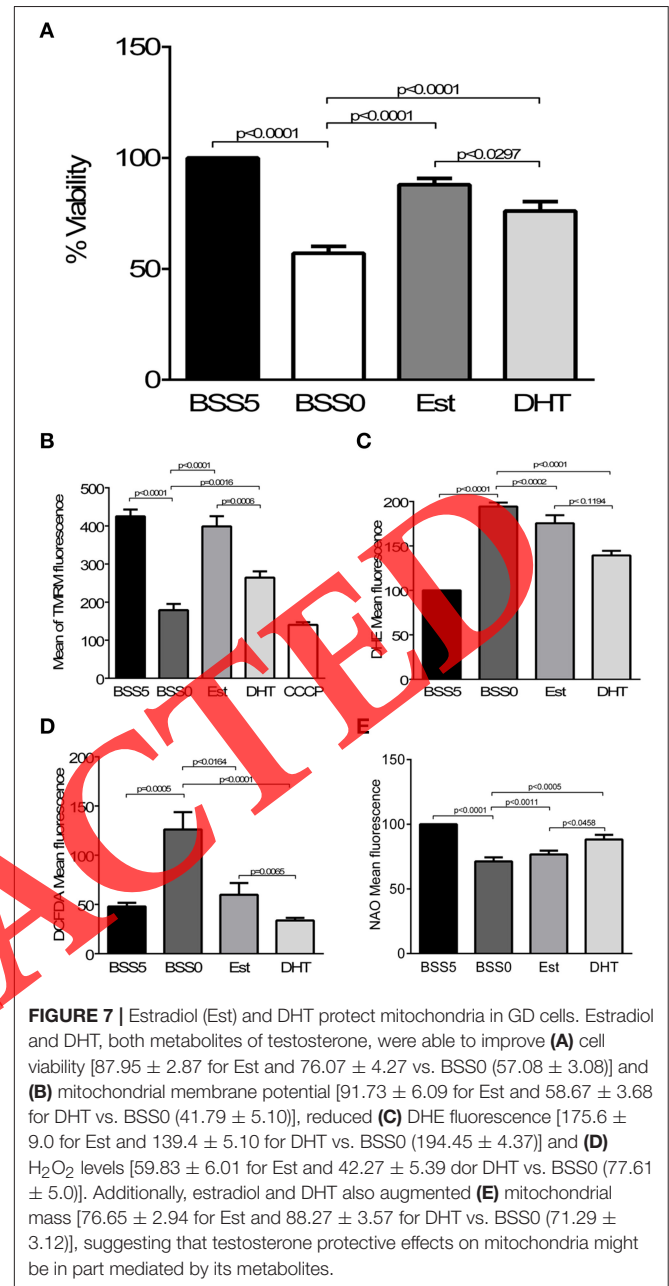
has the ability to induce expression of neuroprotective proteins in damaging conditions. Given the different results described above, it is suggested that the neuroprotective actions by neuroglobin are specifically related to the maintenance of ATP production and other mitochondrial functions (Yu et al., 2013b), the elimination of ROS (Li et al., 2008a,b), and the maintenance of the integrity of the cell membrane (Antao et al., 2010). To determine whether testosterone might exert protective actions on T98G cells through its metabolites, we treated cells with estradiol or DHT. Interestingly, both metabolites have shown to regulate cell survival and improved mitochondrial functions in GD cells (**Figure 7**), thus

demonstrating that testosterone actions on T98G cells subjected to glucose deprivation might be in part mediated by estradiol and DHT.

In conclusion, our results demonstrate the protective effects of testosterone in the astrocytic-like model against GD induced cell death. Furthermore, testosterone was shown to improve and preserve mitochondrial functions and increase the expression of neuroglobin, demonstrating a potential role in modulating ROS production and inducing the expression of neuroprotective proteins.

AUTHOR CONTRIBUTIONS

NT and GB designed the experiments; NT performed the experiments; NT, VE, GB, and LG analyzed the data; GB, LG, and VE wrote the manuscript.

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