Experimental Gerontology 94 (2017) 69–72

Contents lists available at ScienceDirect

Experimental Gerontology

journal homepage: www.elsevier.com/locate/expgero

The influence of vitamins E and C and exercise on brain aging

J. Thomas Mock, Kiran Chaudhari, Akram Sidhu, Nathalie Sumien *

Center for Neuroscience Discovery, Institute for Healthy Aging, University of North Texas Health Science Center at Fort Worth, Fort Worth, TX 76107, USA

ARTICLE INFO

Article history:
Received 30 September 2016
Received in revised form 1 December 2016
Accepted 7 December 2016
Available online 9 December 2016

Keywords:
Exercise
Antioxidants
Brain function
Vitamin E
Vitamin C
Aging
Cognition
Motor function

ABSTRACT

Age-related declines in motor and cognitive function have been associated with increases in oxidative stress. Accordingly, interventions capable of reducing the oxidative burden would be capable of preventing or reducing functional declines occurring during aging. Popular interventions such as antioxidant intake and moderate exercise are often recommended to attain healthy aging and have the capacity to alter redox burden. This review is intended to summarize the outcomes of antioxidant supplementation (more specifically of vitamins C and E) and exercise training on motor and cognitive declines during aging, and on measures of oxidative stress. Additionally, we will address whether co-implementation of these two types of interventions can potentially further their individual benefits. Together, these studies highlight the importance of using translationally-relevant parameters for interventions and to study their combined outcomes on healthy brain aging.

1. Introduction

Aging is associated with a decline in neurophysiological functions including but not limited to motor coordination and activity, memory, cognitive flexibility, and problem-solving ability (Rusinek et al., 2003; Seidler, 2006; Seidler et al., 2010). While the underlying mechanisms associated with declining motor and cognitive function remain unclear, it is known that the brain is particularly vulnerable to oxidative stress due to its high aerobic metabolism rate, abundance of redox modifiable substrates like iron and polyunsaturated fatty acids, relatively low antioxidant capacity, and limited cell turnover and neuroplasticity (Evans, 1993; Klempin and Kempermann, 2007). While some controversy has emerged (Perez et al., 2009), the oxidative stress theory remains an active explanation of the mechanisms underlying aging processes in multiple species and systems (Ferguson and Bridge, 2016; Huang et al., 2015; Sohal and Forster, 2014). In humans and in rodents, studies have provided evidence of increased oxidative stress and oxidative damage in the aging brain (Grimm et al., 2011; Perluigi et al., 2010), and that damage accumulation varied in different regions of the brain (Dubey et al., 1996). Furthermore, protein oxidative damage in the cerebral cortex and in the cerebellum of old mice was found to vary directly with the severity of their cognitive (water maze acquisition) and motor (bridge walking) impairments, respectively (Forster et al., 1996). More recent experiments have used shifts in the redox state of glutathione (GSH:GSSG; reduced glutathione:oxidized glutathione) as a more sensitive indicator of cellular oxidative stress (Sohal and Orr, 2012), and have indicated progressive pro-oxidizing shifts in several brain regions that began as early as 6 months of age (Rebrin et al., 2007). This degree of pro-oxidizing shift seems sufficient to produce redox-dependent cellular dysfunction (Droge and Schipper, 2007), leading to age-related declines in brain function.

According to this hypothesized mechanism, an intervention capable of reducing the oxidative burden or the pro-oxidizing shift would also prevent or delay age-related functional deficits. One dietary intervention that has received extensive scrutiny over several decades and has been shown to reduce oxidative stress and improve brain function is caloric restriction (CR). While these observations have been extensively found in rodents and other species (Dubey et al., 1996; Ingram, 1991), the benefits of CR remain contradictory in humans and non-human primates (Gillette-Guyonnet et al., 2013; Ingram et al., 2007). Additional studies of CR in humans and non-human primates are undergoing and are needed to fully determine the efficacy of CR to improve brain aging. Whereas CR is a promising intervention, its practicality and popularity remain questionable and has led researchers to seek out alternate strategies, such as other lifestyle changes, to improve brain function during aging. Popular interventions such as antioxidant intake and moderate exercise are often recommended to attain healthy brain aging. Both types of intervention have the ability through both shared and independent mechanisms to reduce oxidative stress and improve brain function.

While many antioxidants have been studied, this review will focus primarily on vitamins C and E, as they are readily available, affordable,

* Corresponding author at: Center for Neuroscience Discovery, Institute for Healthy Aging, UNT Health Science Center, 3500 Camp Bowie, Fort Worth, TX 76107, USA.
E-mail address: nathalie.sumien@unthsc.edu (N. Sumien).

http://dx.doi.org/10.1016/j.exger.2016.12.008
0531-5565/

frequently taken as supplements and have been used, alone or in combination, in many studies of brain aging. Furthermore, they have other advantages when used together: (i) they each protect a different cellular fraction (membrane vs. cytosol), and (ii) there exists a recycling mechanism in which oxidized vitamin E is reduced by vitamin C. The effects of moderate exercise on age-related declines in motor and cognitive function will also be described. Finally, this review will highlight the current findings on the outcomes of combining antioxidant intake with moderate exercise and whether precautions should be taken when implementing interventions to delay age-related declines in motor and cognitive function.

2. Antioxidant intake and moderate exercise as interventions against brain aging

2.1. Single antioxidant supplementation

Vitamin E, or α-tocopherol (the most commonly used form), is the most potent antioxidant found in the cellular membrane capable of stopping the propagation of lipid peroxidation, and has been shown to accumulate in brain tissues upon supplementation (Sumien et al., 2003). Over the years, studies of vitamin E supplementation have led to the overall conclusion that vitamin E alone does not infer much protection against brain aging and neurodegenerative diseases. However, it is important to highlight that differences in studies may explain the disparities in outcomes, and the lack of translation in randomized clinical trials (RCTs). In rodents, differential outcomes may be explained by the use of different isoforms of α-tocopherol (synthetic (Sumien et al., 2004) vs. natural (Shetty et al., 2014)), and by the age at which the supplementation was started. Indeed, when vitamin E is introduced in younger subjects and maintained into advanced age, improvements in cognitive and motor performance as well as decrease in oxidative stress were observed (Joseph et al., 1998); however senescence-initiated vitamin E supplementation did not reverse oxidative damage or improve brain function (Sumien et al., 2004). In human studies, the outcomes of vitamin E supplementation were also disappointing with little to no effect reported in RCTs (Gilgun-Sherki et al., 2001). However, with advancement in the understanding of the biochemistry and roles of vitamin E (Joshi and Pratico, 2012), along with reconsidering basic interventional studies parameters (use of translational relevance in setting dosage and timing), more studies will be needed prior to reaching a final conclusion on the usability of vitamin E to improve brain function.

Vitamin C, or ascorbic acid, a potent water-soluble antioxidant found in the cytosol, is responsible for quenching different types of radicals, has the capability to regenerate other antioxidants such as vitamin E and glutathione, and is highly concentrated in the brain (Harrison et al., 2014). Studies on the effects of vitamin C on oxidative stress and brain function in aging and neurodegenerative diseases have also led to inconclusive data on its suitability as an intervention to delay age-related decline in brain function. In rodents, studies have suggested that ascorbic acid supplementation can facilitate learning and memory in old mice (Arzi et al., 2004), and models of Alzheimer's disease (Harrison et al., 2009a; Harrison et al., 2009b). While ascorbic acid's role as an antioxidant has been under scrutiny due to its potential to become a pro-oxidant by means of the Fenton reaction in the presence of metal ions, in vivo studies have vastly supported an antioxidant role (Carr and Frei, 1999; Halliwell, 1996). Animal and humans studies have supported that a deficiency in ascorbic acid was associated with increased oxidative stress (Harrison et al., 2014). Epidemiological studies remain inconclusive on whether dietary intake might affect cognitive status, with some studies showed delay in development of Alzheimer's disease and others reported no effect. The inconclusive nature of these studies is in part due the unreliability of the vitamin C intake reports, as most are self-reported and do not reflect lifetime dietary habits, and might be affected by recall ability which is diminished by age and presence of neurodegenerative diseases (Harrison et al., 2014). Further studies on the association of ascorbic acid with cognitive and motor status will require more reliable measurements of vitamin C intake, such as plasma and cerebrospinal fluid (CSF) levels. CSF:plasma ratio has been predictive of cognitive declines in Alzheimer's disease patients, and more research will be needed to determine the factors influencing the brain's capacity to keep this ratio high and delay functional declines (Bowman, 2012).

Whereas results with individual antioxidant compounds have been relatively disappointing, supplementation involving multiple antioxidants or antioxidant-rich food has consistently yielded positive outcomes (Joseph et al., 2009; Willis et al., 2009). Even combinations of just two or three antioxidants have led to increased beneficial outcomes on learning and to decreased oxidative stress (McDonald et al., 2005; Shetty et al., 2014) when compared to each antioxidant alone. The basic rationale for combining vitamin E and vitamin C stems from their different mechanisms and loci of action, and their interaction within a redox network. Alpha-tocopherol (vitamin E) is found in all biological membranes and is involved in a chain-breaking mechanism to prevent further lipid peroxidation by scavenging peroxyl radicals. In the process, α-tocopherol becomes oxidized to α-tocopheroxyl radical, which can in turn become very damaging. Based on redox potential and availability of the radical located at the membrane water interface, ascorbate, a lipophilic co-antioxidant, can reduce back the tocopheroxyl radical to tocopherol. Ascorbate is then oxidized and is recycled with the help of enzyme systems using NADH or NADPH (Buettner, 1993). The plasma concentrations of vitamins C and E, along with other antioxidants, were found to be depleted in patients with mild cognitive impairments and with Alzheimer's disease (Rinaldi et al., 2003). In rodents, the combination of vitamins C and E has been shown to prevent homocysteine-induced functional impairments (Reis et al., 2002), to reduce age-associated impairments in cognitive function (Arzi et al., 2004), to decrease oxidative stress in the brain of old diabetic rats (Naziroglu et al., 2011), and to protect against intermittent cold exposure-induced oxidative stress in the hypothalamus and cortex of old rats (Asha Devi and Manjula, 2014; Asha Devi et al., 2012). While these studies demonstrated that the combination of the two vitamins is effective in improving brain function and decreasing oxidative stress, most do not systematically compare the stand alone intervention with their combination and therefore do not provide evidence of an additive or synergistic effect. More studies are needed to determine the nature of the interactions between antioxidants on cellular redox state and resulting brain function during aging.

2.2. Physical exercise

The World Health Organization has recommended that older individuals exercise for at least 150 min at moderate intensity or 75 min at vigorous intensity per week to obtain overall health benefits (WHO, 2012). More recently, attention has shifted toward its potential to offer protection against motor and cognitive declines associated with aging. Rodent studies have consistently shown that motor and cognitive declines can be delayed or reversed with regular physical activity. In rodents, exercise has been associated with enhanced muscular function, increased strength, delayed age-related muscular decline, improved cognitive function (Boveris and Navarro, 2008; Merritt and Rhodes, 2015), and enhanced neural plasticity (Cotman et al., 2007). Meta-analyses on exercise outcomes have suggested that endurance and/or strength training improve physical and cognitive functions in elderly adults (Heyn et al., 2004, 2008). Other studies have associated hippocampal plasticity and reversal of the age-related loss of hippocampal volume with exercise training (Duzel et al., 2016; Erickson et al., 2011). Whereas high individual variations are inherent to the response to exercise, most studies have reported that exercise can attenuate motor and cognitive declines associated with aging and dementia (Ahlskog et al., 2011; Kramer et al., 2006; Lautenschlager et al., 2012). While most of these studies have focused on aerobic training, other

work suggests that resistance training can also improve cognition in rodents (Cassilhas et al., 2012) and humans (Ozkaya et al., 2005), and ameliorate muscular strength in humans (Melov et al., 2007) though the underlying mechanisms might diverge (Cassilhas et al., 2012). A varied-mode style of training regimen might be most beneficial (Barnes, 2015), however more studies will be needed to determine the optimal balance of aerobic, strength and flexibility exercise desired to reverse or delay age-related declines in brain function.

While the mechanisms underlying the beneficial effects of exercise on brain function remain to be elucidated, research suggests a strong involvement of neurotrophins, adaptation in vascular physiology, and improved neurovascular coupling (Duzel et al., 2016). Exercise can also act as a mild stressor that promotes adaptations leading to antioxidant defense system fortification, improved mitochondrial function, and induced redox remodeling (Cobley et al., 2015; Navarro et al., 2004; Ristow and Schmeisser, 2014; Tung et al., 2015).

Exercise is a very promising intervention, but can we further enhance its benefits by adding-on other strategies such as cognitive training or other lifestyle interventions?. Previous studies have indicated that the beneficial effects of exercise were enhanced with the co-implementation of cognitive stimulation (Anderson-Hanley et al., 2012; Lautenschlager and Cox, 2013). Plant polyphenols and fatty acids augment the effects of exercise and may involve common cellular mechanisms (van Praag, 2009). Together, previous research suggests that combining of exercise with other therapeutics may provide additional protection.

3. Does combining antioxidant intake and exercise lead to further benefits?

Based on the anticipation of added or synergistic benefits, health conscious individuals may complement their exercise regimen with antioxidant intake (vitamins E and C for the focus of this mini-review) to improve health and retard the effects of aging. However, the nature of the interaction between these two types of interventions remain controversial, and the literature on their combined effect on brain function during aging is rather limited in both humans and rodents (Schattin et al., 2016).

On one hand, the combination of vitamins E with moderate aerobic exercise was associated with a higher increase of antioxidant enzyme activities in the cortex and hippocampus of aged rats than when each intervention was implemented alone (Devi and Kiran, 2004). This same combination also further decreased oxidative damage of proteins and lipids in the brain (Jolitha et al., 2006), and further improved learning in aged rats (Jolitha et al., 2009). Swim training and vitamin E intake co-implementation have also led to improvements in the lipid profile and increased endurance for old rats (Asha Devi et al., 2003). The combination of swimming with a phytotherapeutic enriched in vitamin C reduced oxidative stress and inflammation, and improved learning in a brain injury rat model (Toldy et al., 2005). Together, these studies support a beneficial additive interaction between antioxidants (vitamins C and E) and exercise.

On the other hand, other studies have found either no additive effects of the combination or a negative interaction in which antioxidant supplementation seems to block the beneficial effects of exercise. In adult female rats, lipid peroxidation in the brain was augmented after chronic exercise and vitamin C injections (Coşkun et al., 2005). In studies of mice expressing the human apolipoprotein E4, no additive effect were found on cognitive and affective function (Chaudhari et al., 2014) and an antagonistic interaction on strength measurement was detected in young mice (Chaudhari et al., 2016). The benefits of exercise were blocked by antioxidant intake on arterial atherosclerosis in old mice (Meilhac et al., 2001). In humans, the intake of vitamins blunted the beneficial effects of exercise on type 2 diabetes mellitus and insulin resistance (Ristow et al., 2009), and on endothelial function and blood pressure in mildly hypertensive men (Wray et al., 2009). In summary, the studies indicate that antioxidant intake may limit exercise-induced adaptations and prevent improvements in health.

4. Concluding remarks

With the graying of the world and its increased burden on quality of life and increased health care costs, it is important to identify strategies that increase healthspan by slowing down aging and lowering the incidence of age-associated diseases. Historically, effects from many pre-clinical studies did not translate into clinical settings, especially with antioxidants studies. Some of these false-positive intervention strategies might have been due to an oversight on factors that may have major effects on the outcomes of such interventions. Such factors that will require more attention in future pre-clinical studies are sex, age, duration of the intervention, dosage and formulation of the antioxidants, intensity and mode of exercise, and genetic background (presence or absence of some genes may interact with interventions as seen with APOE4 and exercise (Brown et al., 2013)). In closing, future studies should focus on the functional outcomes and cellular mechanisms underlying the outcomes of combining interventions (i.e. antioxidants and exercise, caloric restriction and exercise) to determine the nature of the interactions between interventions and identify optimal prevention strategies that are easily and readily implemented to reduce the effects of aging and neurodegenerative diseases.

Funding

This work was supported by the National Institutes of Health/National Institute on Aging (P01 AG027956; P01 AG022550; T32 AG020494), by the Alzheimer's Association (NIRG-10-17398), and by a generous grant from the Pine Family Foundation.

References

Ahlskog, J.E., Geda, Y.E., Graff-Radford, N.R., Petersen, R.C., 2011. Physical exercise as a preventive or disease-modifying treatment of dementia and brain aging. Mayo Clin. Proc. 86, 876–884.

Anderson-Hanley, C., Arciero, P.J., Brickman, A.M., Nimon, J.P., Okuma, N., Westen, S.C., Merz, M.E., Pence, B.D., Woods, J.A., Kramer, A.F., Zimmerman, E.A., 2012. Exergaming and older adult cognition: a cluster randomized clinical trial. Am. J. Prev. Med. 42, 109–119.

Arzi, A., Hemmati, A.A., Razian, A., 2004. Effect of vitamins C and E on cognitive function in mouse. Pharmacol. Res. 49, 249–252.

Asha Devi, S., Manjula, K.R., 2014. Intermittent cold-induced hippocampal oxidative stress is associated with changes in the plasma lipid composition and is modifiable by vitamins C and E in old rats. Neurochem. Int. 74, 46–52.

Asha Devi, S., Manjula, K.R., Subramanyam, M.V., 2012. Protective role of vitamins E and C against oxidative stress caused by intermittent cold exposure in aging rat's frontoparietal cortex. Neurosci. Lett. 529, 155–160.

Asha Devi, S., Prathima, S., Subramanyam, M.V., 2003. Dietary vitamin E and physical exercise: I. Altered endurance capacity and plasma lipid profile in ageing rats. Exp. Gerontol. 38, 285–290.

Barnes, J.N., 2015. Exercise, cognitive function, and aging. Adv. Physiol. Educ. 39, 55–62.

Boveris, A., Navarro, A., 2008. Systemic and mitochondrial adaptive responses to moderate exercise in rodents. Free Radic. Biol. Med. 44, 224–229.

Bowman, G.L., 2012. Ascorbic acid, cognitive function, and Alzheimer's disease: a current review and future direction. Biofactors 38, 114–122.

Brown, B.M., Peiffer, J.J., Taddei, K., Lui, J.K., Laws, S.M., Gupta, V.B., Taddei, T., Ward, V.K., Rodrigues, M.A., Burnham, S., Rainey-Smith, S.R., Villemagne, V.L., Bush, A., Ellis, K.A., Masters, C.L., Ames, D., Macaulay, S.L., Szoeke, C., Rowe, C.C., Martins, R.N., 2013. Physical activity and amyloid-beta plasma and brain levels: results from the Australian imaging, biomarkers and lifestyle study of ageing. Mol. Psychiatry 18, 875–881.

Buettner, G.R., 1993. The pecking order of free radicals and antioxidants: lipid peroxidation, a-tocopherol, and ascorbate. Arch. Biochem. Biophys. 300, 535–543.

Carr, A., Frei, B., 1999. Does vitamin C act as a pro-oxidant under physiological conditions? FASEB J. 13, 1007–1024.

Cassilhas, R.C., Lee, K.S., Fernandes, J., Oliveira, M.G., Tufik, S., Meeusen, R., de Mello, M.T., 2012. Spatial memory is improved by aerobic and resistance exercise through divergent molecular mechanisms. Neuroscience 202, 309–317.

Chaudhari, K., Wong, J.M., Vann, P.H., Sumien, N., 2014. Exercise training and antioxidant supplementation independently improve cognitive function in adult male and female GFAP-*APOE* mice. J. Sport Health Sci. 3, 196–205.

Chaudhari, K., Wong, J.M., Vann, P.H., Sumien, N., 2016. Exercise, but not antioxidants, reversed ApoE4-associated motor impairments in adult GFAP-ApoE mice. Behav. Brain Res. 305, 37–45.

Cobley, J.N., Moult, P.R., Burniston, J.G., Morton, J.P., Close, G.L., 2015. Exercise improves mitochondrial and redox-regulated stress responses in the elderly: better late than never! Biogerontology 16, 249–264.
Coşkun, Ş., Gönül, B., Güzel, N.A., Balabanlí, B., 2005. The effects of vitamin C supplementation on oxidative stress and antioxidant content in the brains of chronically exercised rats. Mol. Cell. Biochem. 280, 135–138.
Cotman, C.W., Berchtold, N.C., Christie, L.A., 2007. Exercise builds brain health: key roles of growth factor cascades and inflammation. Trends Neurosci. 30, 464–472.
Devi, A., Kiran, T., 2004. Regional responses in antioxidant system to exercise training and dietary vitamin E in aging rat brain. Neurobiol. Aging 25, 501–508.
Droge, W., Schipper, H.M., 2007. Oxidative stress and aberrant signaling in aging and cognitive decline. Aging Cell 6, 361–370.
Dubey, A., Forster, M.J., Lal, H., Sohal, R.S., 1996. Effect of age and caloric intake on protein oxidation in different brain regions and on behavioral functions of the mouse. Arch. Biochem. Biophys. 333, 189–197.
Duzel, E., van Praag, H., Sendtner, M., 2016. Can physical exercise in old age improve memory and hippocampal function? Brain J. Neurol. 139, 662–673.
Erickson, K.I., Voss, M.W., Prakash, R.S., Basak, C., Szabo, A., Chaddock, L., Kim, J.S., Heo, S., Alves, H., White, S.M., Wojcicki, T.R., Mailey, E., Vieira, V.J., Martin, S.A., Pence, B.D., Woods, J.A., McAuley, E., Kramer, A.F., 2011. Exercise training increases size of hippocampus and improves memory. Proc. Natl. Acad. Sci. U. S. A. 108, 3017–3022.
Evans, P.H., 1993. Free radicals in brain metabolism and pathology. Br. Med. Bull. 49, 577–587.
Ferguson, G., Bridge, W., 2016. Glutamate cysteine ligase and the age-related decline in cellular glutathione: the therapeutic potential of gamma-glutamylcysteine. Arch. Biochem. Biophys. 593, 12–23.
Forster, M.J., Dubey, A., Dawson, K.M., Stutts, W.A., Lal, H., Sohal, R.S., 1996. Age-related losses of cognitive function and motor skills in mice are associated with oxidative protein damage in the brain. Proc. Natl. Acad. Sci. U. S. A. 93, 4765–4769.
Gilgun-Sherki, Y., Melamed, E., Offen, D., 2001. Oxidative stress induced-neurodegenerative diseases: the need for antioxidants that penetrate the blood brain barrier. Neuropharmacology 40, 959–975.
Gillette-Guyonnet, S., Secher, M., Vellas, B., 2013. Nutrition and neurodegeneration: epidemiological evidence and challenges for future research. Br. J. Clin. Pharmacol. 75, 738–755.
Grimm, S., Hoehn, A., Davies, K.J., Grune, T., 2011. Protein oxidative modifications in the ageing brain: consequence for the onset of neurodegenerative disease. Free Radic. Res. 45, 73–88.
Halliwell, B., 1996. Vitamin C: antioxidant or pro-oxidant in vivo? Free Radic. Res. 25, 439–454.
Harrison, F.E., Hosseini, A.H., Dawes, S.M., Weaver, S., May, J.M., 2009a. Ascorbic acid attenuates scopolamine-induced spatial learning deficits in the water maze. Behav. Brain Res. 205, 550–558.
Harrison, F.E., Hosseini, A.H., McDonald, M.P., May, J.M., 2009b. Vitamin C reduces spatial learning deficits in middle-aged and very old APP/PSEN1 transgenic and wild-type mice. Pharmacol. Biochem. Behav. 93, 443–450.
Harrison, F.E., Bowman, G.L., Polidori, M.C., 2014. Ascorbic acid and the brain: rationale for the use against cognitive decline. Nutrients 6, 1752–1781.
Heyn, P., Abreu, B.C., Ottenbacher, K.J., 2004. The effects of exercise training on elderly persons with cognitive impairment and dementia: a meta-analysis. Arch. Phys. Med. Rehabil. 85, 1694–1704.
Heyn, P.C., Johnson, K.E., Kramer, A.F., 2008. Endurance and strength training outcomes on cognitively impaired and cognitively intact older adults: a meta-analysis. J. Nutr. Health Aging 12, 401–409.
Huang, T.T., Leu, D., Zou, Y., 2015. Oxidative stress and redox regulation on hippocampal-dependent cognitive functions. Arch. Biochem. Biophys. 576, 2–7.
Ingram, D.K., 1991. Behavioral and neurobiological effects of dietary restriction in aged rodents. In: Fishbein, L. (Ed.), Biological Effects of Dietary Restriction. Springer-Verlag, Berlin.
Ingram, D.K., Young, J., Mattison, J.A., 2007. Calorie restriction in nonhuman primates: assessing effects on brain and behavioral aging. Neuroscience 145, 1359–1364.
Jolitha, A.B., Subramanyam, M.V., Asha Devi, S., 2006. Modification by vitamin E and exercise of oxidative stress in regions of aging rat brain: studies on superoxide dismutase isoenzymes and protein oxidation status. Exp. Gerontol. 41, 753–763.
Jolitha, A.B., Subramanyam, M.V., Asha Devi, S., 2009. Age-related responses of the rat cerebral cortex: influence of vitamin E and exercise on the cholinergic system. Biogerontology 10, 53–63.
Joseph, J., Cole, G., Head, E., Ingram, D., 2009. Nutrition, brain aging, and neurodegeneration. J. Neurosci. 29, 12795–12801.
Joseph, J.A., Shukitt-Hale, B., Denisova, N.A., Prior, R.L., Cao, G., Martin, A., Taglialatela, G., Bickford, P.C., 1998. Long-term dietary strawberry, spinach, or vitamin E supplementation retards the onset of age-related neuronal signal-transduction and cognitive behavioral deficits. J. Neurosci. 18, 8047–8055.
Joshi, Y.B., Pratico, D., 2012. Vitamin E in aging, dementia, and Alzheimer's disease. Biofactors 38, 90–97.
Klempin, F., Kempermann, G., 2007. Adult hippocampal neurogenesis and aging. Eur. Arch. Psychiatry Clin. Neurosci. 257, 271–280.
Kramer, A.F., Erickson, K.I., Colcombe, S.J., 2006. Exercise, cognition, and the aging brain. J. Appl. Physiol. (1985) 101, 1237–1242.
Lautenschlager, N.T., Cox, K.L., 2013. Can participation in mental and physical activity protect cognition in old age?: comment on "The Mental Activity and eXercise (MAX) trial: a randomized controlled trial to enhance cognitive function in older adults". JAMA Intern. Med. 173, 805–806.
Lautenschlager, N.T., Cox, K., Cyarto, E.V., 2012. The influence of exercise on brain aging and dementia. Biochim. Biophys. Acta 1822, 474–481.
McDonald, S.R., Sohal, R.S., Forster, M.J., 2005. Concurrent administration of coenzyme Q10 and alpha-tocopherol improves learning in aged mice. Free Radic. Biol. Med. 38, 729–736.
Meilhac, O., Ramachandran, S., Chiang, K., Santanam, N., Parthasarathy, S., 2001. Role of arterial wall antioxidant defense in beneficial effects of exercise on atherosclerosis in mice. Arterioscler. Thromb. Vasc. Biol. 21, 1681–1688.
Melov, S., Tarnopolsky, M.A., Beckman, K., Felkey, K., Hubbard, A., 2007. Resistance exercise reverses aging in human skeletal muscle. PLoS One 2, e465.
Merritt, J.R., Rhodes, J.S., 2015. Mouse genetic differences in voluntary wheel running, adult hippocampal neurogenesis and learning on the multi-strain-adapted plus water maze. Behav. Brain Res. 280, 62–71.
Navarro, A., Gomez, C., Lopez-Cepero, J.M., Boveris, A., 2004. Beneficial effects of moderate exercise on mice aging: survival, behavior, oxidative stress, and mitochondrial electron transfer. Am. J. Phys. Regul. Integr. Comp. Phys. 286, R505–R511.
Naziroglu, M., Butterworth, P.J., Sonmez, T.T., 2011. Dietary vitamin C and E modulates antioxidant levels in blood, brain, liver, muscle, and testes in diabetic aged rats. Int. J. Vitam. Nutr. Res. 81, 347–357.
Ozkaya, G.Y., Aydin, H., Toraman, F.N., Kizilay, F., Ozdemir, O., Cetinkaya, V., 2005. Effect of strength and endurance training on cognition in older people. J. Sports Sci. Med. 4, 300–313.
Perez, V.I., Bokov, A., Van Remmen, H., Mele, J., Ran, Q., Ikeno, Y., Richardson, A., 2009. Is the oxidative stress theory of aging dead? Biochim. Biophys. Acta 1790, 1005–1014.
Perluigi, M., Di Domenico, F., Giorgi, A., Schinina, M.E., Coccia, R., Cini, C., Bellia, F., Cambria, M.T., Cornelius, C., Butterfield, D.A., Calabrese, V., 2010. Redox proteomics in aging rat brain: involvement of mitochondrial reduced glutathione status and mitochondrial protein oxidation in the aging process. J. Neurosci. Res. 88, 3498–3507.
Rebrin, I., Forster, M.J., Sohal, R.S., 2007. Effects of age and caloric intake on glutathione redox state in different brain regions of C57BL/6 and DBA/2 mice. Brain Res. 1127, 10–18.
Reis, E.A., Zugno, A.I., Franzon, R., Tagliari, B., Matte, C., Lammers, M.L., Netto, C.A., Wyse, A.T., 2002. Pretreatment with vitamins E and C prevent the impairment of memory caused by homocysteine administration in rats. Metab. Brain Dis. 17, 211–217.
Rinaldi, P., Polidori, M.C., Metastasio, A., Mariani, E., Mattioli, P., Cherubini, A., Catani, M., Cecchetti, R., Senin, U., Mecocci, P., 2003. Plasma antioxidants are similarly depleted in mild cognitive impairment and in Alzheimer's disease. Neurobiol. Aging 24, 915–919.
Ristow, M., Schmeisser, K., 2014. Mitohormesis: promoting health and lifespan by increased levels of reactive oxygen species (ROS). Dose-Response 12, 288–341.
Ristow, M., Zarse, K., Oberbach, A., Kloting, N., Birringer, M., Kiehntopf, M., Stumvoll, M., Kahn, C.R., Bluher, M., 2009. Antioxidants prevent health-promoting effects of physical exercise in humans. Proc. Natl. Acad. Sci. U. S. A. 106, 8665–8670.
Rusinek, H., De Santi, S., Frid, D., Tsui, W.H., Tarshish, C.Y., Convit, A., de Leon, M.J., 2003. Regional brain atrophy rate predicts future cognitive decline: 6-year longitudinal MR imaging study of normal aging. Radiology 229, 691–696.
Schattin, A., Baur, K., Stutz, J., Wolf, P., de Bruin, E.D., 2016. Effects of physical exercise combined with nutritional supplements on aging brain related structures and functions: a systematic review. Front. Aging Neurosci. 8, 161.
Seidler, R.D., 2006. Differential effects of age on sequence learning and sensorimotor adaptation. Brain Res. Bull. 70, 337–346.
Seidler, R.D., Bernard, J.A., Burutolu, T.B., Fling, B.W., Gordon, M.T., Gwin, J.T., Kwak, Y., Lipps, D.B., 2010. Motor control and aging: links to age-related brain structural, functional, and biochemical effects. Neurosci. Biobehav. Rev. 34, 721–733.
Shetty, R.A., Ikonne, U.S., Forster, M.J., Sumien, N., 2014. Coenzyme Q10 and alpha-tocopherol reversed age-associated functional impairments in mice. Exp. Gerontol. 58, 208–218.
Sohal, R.S., Forster, M.J., 2014. Caloric restriction and the aging process: a critique. Free Radic. Biol. Med. 73, 366–382.
Sohal, R.S., Orr, W.C., 2012. The redox stress hypothesis of aging. Free Radic. Biol. Med. 52, 539–555.
Sumien, N., Forster, M.J., Sohal, R.S., 2003. Supplementation with vitamin E fails to attenuate oxidative damage in aged mice. Exp. Gerontol. 38, 699–704.
Sumien, N., Heinrich, K.R., Sohal, R.S., Forster, M.J., 2004. Short-term vitamin E intake fails to improve cognitive or psychomotor performance of aged mice. Free Radic. Biol. Med. 36, 1424–1433.
Toldy, A., Stadler, K., Sasvari, M., Jakus, J., Jung, K.J., Chung, H.Y., Berkes, I., Nyakas, C., Radak, Z., 2005. The effect of exercise and nettle supplementation on oxidative stress markers in the rat brain. Brain Res. Bull. 65, 487–493.
Tung, B.T., Rodriguez-Bies, E., Thanh, H.N., Le-Thi-Thu, H., Navas, P., Sanchez, V.M., Lopez-Lluch, G., 2015. Organ and tissue-dependent effect of resveratrol and exercise on antioxidant defenses of old mice. Aging Clin. Exp. Res. 27, 775–783.
van Praag, H., 2009. Exercise and the brain: something to chew on. Trends Neurosci. 32, 283–290.
WHO, 2012. Global Recommendations on Physical Activity for Health. WHO Press, Geneva.
Willis, L.M., Shukitt-Hale, B., Joseph, J.A., 2009. Modulation of cognition and behavior in aged animals: role for antioxidant- and essential fatty acid-rich plant foods. Am. J. Clin. Nutr. 89, 1602S–1606S.
Wray, D.W., Uberoi, A., Lawrenson, L., Bailey, D.M., Richardson, R.S., 2009. Oral antioxidants and cardiovascular health in the exercise-trained and untrained elderly: a radically different outcome. Clin. Sci. (Lond.) 116, 433–441.