



Effect of gabapentin on fetal rat brain and its amelioration by ginger

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ABSTRACT

Intrauterine exposure to antiepileptic drugs (AEDs) is associated with neurodevelopmental alterations causing postnatal behavioral and cognitive alterations. These disorders are associated with the interference of these AEDs with the developing cerebral cortex and hippocampal neurons. Therefore, it is crucial to identify the drugs that should be avoided during pregnancy in order to prevent AED mediated developmental alterations. The present study was conducted to investigate the effects of prenatal exposure to the antiepileptic drug gabapentin (GBP) on the rat fetal brain during the organogenesis phase and to examine the potential ameliorative effect of ginger (*Zingiber officinale*). Consequently, the current study addressed the developmental neural changes on the histological, immuno-histochemical and ultrastructural levels. The brain of fetuses from the GBP group showed a highly significant decrease in their weight. Histologically, the cerebral cortex and hippocampus regions of fetuses maternally injected with GBP showed layer disorganization, vacuolated neuropil and massive cell degeneration. The expression of Caspase 3 was significantly increased in the brain of GBP fetuses, unlike the expression of Bcl-2 which was significantly decreased. On the ultrastructure level, the neurons showed pyknotic and chromatolytic nuclei. The cytoplasm was rarefied with swollen organelles. Co-administration of ginger evidently ameliorated most of these effects. In conclusion, GBP administration during pregnancy could possibly affect the developing fetal brain and ginger may have ameliorating effect against the induced GBP neurotoxicity and should be taken in parallel.

1. Introduction

Epilepsy is a condition characterized by abnormal excessive synchronous neuronal activity in the brain causing seizures (Fisher et al., 2005), and is associated with a variety of neurobiological, psychological, social and cognitive consequences (Macfarlane; Greenhalgh, 2018). Women with epilepsy receiving antiepileptic drugs (AEDs) are known to be at a greater risk of having seizures during pregnancy, as well as other complications (miscarriage, preterm labour, low birth weight, and maternal or fetal death); their offspring are more likely to have congenital malformations or developmental delays and increased risk of teratogenicity (Sveberg et al., 2015). Unfortunately, epileptic pregnant women typically continue treatment with AEDs during pregnancy to avoid the potential harmful effect of recurrent seizures which can have significant long term neurological and physical consequences to both themselves and their fetuses (Gilboa et al., 2011; Ban et al., 2015). Maintaining the balance between convenient seizure control during pregnancy and the teratogenic risk of AEDs is a major obstacle for neurologists (Ferri et al., 2018).

The most common congenital defects related to AEDs include neural tube defects, intrauterine growth retardation (IUGR), developmental delay and microcephaly (Meador et al., 2006; Soysal et al., 2011). There is a potential risk that continuous exposure of epileptic women to the drug might result in considerable accumulation of the drug in the embryo during the preimplantation period, by which time the pregnancy might not have been recognized (Padmanabhan et al., 2008).

It has been reported that in utero exposure to AEDs may cause an increased incidence of congenital anomalies affecting a variety of organs, including the central nervous system (CNS) (Verrotti et al., 2014). Many old generation AEDs, such as phenytoin and phenobarbital, induce massive apoptotic neuronal death in specific brain regions during the first two postnatal weeks in rats (Bittigau et al., 2002; Olney et al., 2004). Women receiving AED treatment during pregnancy are most likely known to experience disorders of primary neurulation, one of which is open neural tube defects of the offspring (Özer et al., 2012). In utero exposure of rats to valproic acid causes cerebellar anomalies (Ikonomidou and Turski, 2009).

Gabapentin (GBP) is a new generation AED designed to treat partial

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seizures and is a γ -aminobutyric acid analog that differs both structurally and pharmacologically from other classes of antiepileptic drugs. GBP was approved by the US Food and Drug Administration for use in epilepsy in 1993 and subsequently for neuropathic pain in 2002. Gabapentin was described to be one of the most used antiepileptic drugs along with pregabalin, carbamazepine and lamotrigine, accounting for more than 60% of the total AED consumption in Norway as demonstrated by the study of (Halvorsen et al., 2016). According to recent updated treatment guidelines, gabapentin and lamotrigine have a level A evidence for the treatment of focal epilepsies in the elderly (Glauser et al., 2013). Despite the increasing number of patients receiving GBP, there is only limited information regarding its safety during pregnancy, therefore more information regarding fetal safety is required (Fujii et al., 2013).

Medicinal plants are now extensively used in curing most diseases (Johari et al., 2013). Ginger is one of the important medicinal plants that has a long history in traditional medicine for conditions such as headaches, toothache, colds, improvement of circulation of the limbs and lowering blood cholesterol (Zahedi et al., 2012). In addition, ginger extract is known to have strong antioxidant activity (Nanjundaiah et al., 2011) and neuroprotective effect (Waggas, 2009).

The present study was designed firstly, to investigate the possible fetal neurotoxic side effects of prenatal exposure to GBP during the organogenesis phase of the embryonic development in rat fetuses. Secondly, to examine the possible ameliorative role of ginger against the GBP induced toxicity through histological, immune-histochemical and ultrastructural investigations.

2. Materials and methods

2.1. Animals and grouping

Principles of animal care and use were carefully followed during conducting the present study according to the guide for the care and use of laboratory animals approved by Faculty of Science, Menoufia University, Egypt (Approval No. MNSE2180) and according to the National Institutes of Health guide for the care and use of Laboratory animals (NIH Publications No. 8023, revised 1978). Thirty-six healthy mature fertile males (12) and virgin females (24) of Westar albino rats (*Rattus norvegicus*), weighing 235 ± 15 g and aged 17 ± 1 weeks, were obtained from Vacsera (Hellwan Animal Breeding Farm), Ministry of Health, Cairo, Egypt. Rats were kept in the laboratory for two weeks before initiation of the experiments for acclimatization. They were housed in specially designed plastic rodent cages at Faculty of Science, Menoufia University and maintained at $25 \pm 2^\circ\text{C}$ in 12h light: 12h dark cycle. Free access of water and standard diet composed of 50% ground barely, 20% ground yellow maize, 20% milk and 10% vegetables were supplied. Mating was achieved by housing two females with one male overnight. Daily vaginal smears were carried out to give a precise determination of the onset of gestation. The day at which vaginal smear was positive has been considered as the day zero of pregnancy. Day 20 was determined as the end point for experimentation. The pregnant rats were divided into four groups, six rats each, as follows:

1. Control group, administrated 1 ml distilled water, intraperitoneally.
2. Ginger administrated group given oral dose of ginger (200 mg/kg).
3. Experimental GBP group given intraperitoneal injection of GBP (162 mg/kg).
4. Combined GBP and ginger injected group, received intraperitoneal injection of GBP first followed by oral administration of ginger 1 h later.

This study was based on 36 fetuses.

2.2. Gabapentin

GBP, with the trade name Gaptin (Delta Pharma Company, Egypt)

was employed for the study. GBP in doses of 81, 162 or 324 mg/kg body weight equivalent to 900, 1800 or 3600 mg, respectively of the adult human dose (dosages for rat were calculated as described by Paget and Barnes, 1964) were experimented (Prakash et al., 2008). After many trials, it was found that the mid dose, 162 mg/kg was the most convenient one, as the low dose didn't induce any alterations and the high dose resulted in high mortality rate. Accordingly, Gaptin capsules of 300 mg/kg concentration were used. The capsules were emptied and the powder was weighed and dissolved in 1 ml distilled water and intraperitoneally injected per day using insulin syringe during the organogenesis phase of gestation, i.e. starting on GD 6 and ending on GD 15.

2.3. Ginger extract

Fresh rhizomes of *Zingiber officinale* were purchased from a local market at Shebeen El-Koom, Menoufia, Egypt. The extract was prepared according to Badawy et al. (2019). Briefly, fresh rhizomes of ginger (*Zingiber officinale*) were shade dried at room temperature and then crushed to powder. 125 g of the powder were macerated in 1000 ml of distilled water for 12 h at room temperature and filtered through a 5 μm filter paper to obtain the final aqueous extract. Accordingly, concentration of the obtained extract was 24 mg/ml. Ginger extract was daily administrated orally, 1 h after GBP injection, by gavage tube at a dose of 200 mg/kg body weight (Abd El-Aty and Morgan, 2011) during the organogenesis phase of gestation, i.e. from GD 6 to GD 15.

2.4. Investigated parameters

2.4.1. Morphometric parameters

2.4.1.1. Brain weight. The weight (g) of the brain of fetuses of different groups was recorded.

2.4.2. Histological examination

For light microscopical examination, the brain of fetuses of the different groups was fixed by immersion in Bouin's solution for 24 h at room temperature. Fixation was followed by 3 successive changes of 70 % ethanol.

All specimens were transferred to 70 % ethanol and then dehydrated in an ascending series of ethanol, cleared in xylol and embedded in molten paraffin.

Five μm thick sections were produced using a rotary microtome (Leica, Model Rm 2125, Germany). Sections were mounted on albumen-coated slides and stored until staining. Histological staining was performed with Ehrlich's hematoxylin and counterstained with aqueous eosin. Microscopical examination and photographing of the histological sections were adopted using Olympus microscope (BX41).

2.4.3. Immuno-histochemical investigation

Avidin-biotin peroxidase method was used for the immuno-histochemical demonstration of the proapoptotic antigen Caspase-3 and anti-apoptotic mediator Bcl-2. Samples of the fetal brain were fixed in 10 % formalin for 24 h (Sternberger, 2006; Hussein and Ahmed, 2010). The presence of Bcl-2 and Caspase-3 proteins was confirmed by the presence of a dark, brownish, intracytoplasmic precipitate.

All stained slides were viewed using Olympus microscope (BX41) and images were captured by a digital camera (Canon Power Shot A620). Digital images were analyzed by a semi-quantitative scoring system (Fig-Image J software, Java based application for analyzing images) (Schindelin et al., 2012).

2.4.4. Ultrastructural investigation

For ultrastructural investigation, which has been done using transmission electron microscope, specimens of fetal brain of both control and

experimental groups were separated and immediately fixed for 4 h at room temperature in 2.5% Glutaraldehyde and 2% paraformaldehyde in 0.1 cacodylate buffer (PH. 7.4) and processed as described in Badawy et al. (2019).

2.4.5. Data evaluation and statistical analysis

All data sets were expressed as mean $\pm$ standard error of the mean (SEM). The data were analyzed statistically for normal distribution (student's T test) and homogeneity of variances (Levene test) independent-samples T test using statistical program of social sciences (IBM SPSS) statistics software for Windows, Version 22 (IBM Corp., Armonk, NY, USA). Differences were considered insignificant whenever $p > 0.05$. The significances of the obtained data were classified into two categories, i.e. $p < 0.0001$ and $p < 0.05$ according to the obtained p values.

3. Results

3.1. Fetal brain weight

Fig. (1) illustrates the changes in brain weight of fetuses aged 20 days in control and experimental groups. The fetuses of the control and maternally ginger administered groups had very close values. There was a highly significant decrease in the brain weight of fetuses of the maternally GBP injected group. On the other hand, the fetuses maternally injected with GBP and ginger together displayed a significant increase in the brain weight compared with GBP alone.

3.2. Histological investigations

3.2.1. Control group

Fig. (2A) showed the histological structure of the cerebral cortex of control fetuses. The developing cerebral cortex showed five basic histological zones. These zones, from outwards inwards were marginal zone (MZ), cortical plate (CP), intermediate zone (IZ), subventricular zone (SVZ) and ventricular zone (VZ). The MZ was relatively acellular, while the CP was cell-dense and formed of closely packed rounded or oval-shaped neuronal cells. The IZ was deep to the CP. It was discriminable by linear arrays of cells. Two deepest zones, the VZ and the SVZ were densely packed with cell bodies. The VZ consisted of pseudostratified columnar epithelium and was located close to the ventricular cavity of the brain, where cells actively proliferated, while the SVZ contained more haphazardly arranged cell bodies. Different types of cells found in the cerebral cortex were illustrated in Fig. (2B). These cells included granular, pyramidal, astrocytes and microglial cells. The neuropil appeared homogenous and was in the form of a mat of neuronal and glial cell processes. The structure of hippocampus is illustrated in Fig. (2C) and appeared as a C-shaped structure, positioned posteriorly in the

hemisphere of the rat brain. It encompassed four main subfields with the dentate gyrus (DG) as the most medial and proximal portion, laterally flanked by the *cornu ammonis* (CA) with its three subfields (CA1, CA2, CA3). The CA1 and DG regions were formed of granular cells, while the CA3 region was formed of pyramidal cells. Fig. (2D) showed the structure of the CA1 layer of hippocampus which was formed mostly of granule cells besides other cells (Fig. 2D).

3.2.2. Ginger group

Fetuses maternally injected with ginger alone showed normal cerebral cortical and hippocampal structure similar to that of the control group (Fig. 2E-G).

3.2.3. GBP group

The cerebral cortex of fetuses maternally injected with GBP showed disrupted layer architecture comparing with the control. Hypoplasia of the cells of the cortical, subventricular and ventricular zones and reduction in the cortical and subventricular zones were seen as well as narrowing and irregularity in the lateral ventricle. Cell necrosis was detected in different zones of the cerebral cortex (Fig. 2H). Pyknosis was the most prominent feature of the neuronal nuclei. Some of the nuclei showed karyorrhexis and karyolysis appearance. In addition to evident micro-vacuolation of the neuropil (Fig. 2I).

The hippocampal areas manifested massive neuronal cell degeneration, especially in the CA1 area. The neurons were shrunken and darkly stained with small and pyknotic nuclei. Vacuolation was evident in the neuropil (Fig. 2J).

3.2.4. GBP + ginger group

Fetuses maternally injected with GBP followed by ginger exhibited amelioration of the histological structure of both cerebral cortex and hippocampus (Fig. 2K&L). Most of pyramidal and granule cells of the cerebral cortex were nearly similar to that of the control group. The majority of cells appeared normal with no signs of pyknosis, karyorrhexis or karyolysis signs, however, few cells were more darkly stained and the neuropil was homogenous (Fig. 2K).

Amelioration of hippocampus, especially the CA1 sub region, was detected in those fetuses and almost restored the structural pattern of fetuses of the control group. The neuropil restored its normal pattern with no signs of vacuolation (Fig. 2L).

3.3. Immuno-histochemical investigation

The expression of the anti-apoptotic protein Bcl-2 and pro-apoptotic protein Caspase-3 in the fetal brain of different groups were adopted for detection of apoptosis.

Immuno-histochemical investigation of neuronal tissues indicated that expression of the Bcl-2 and Caspase-3 antigens was restricted to the

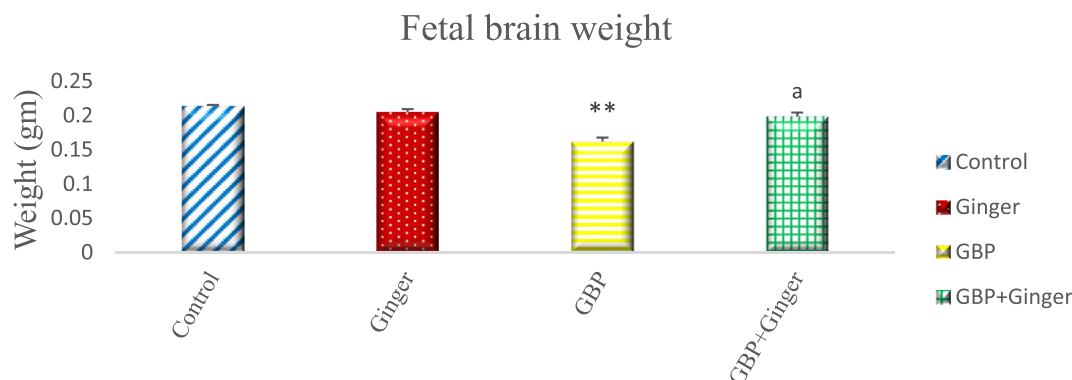


Fig. 1. Graph showing the brain weight of 20-day-old rat fetuses in different groups. Data are represented as mean $\pm$ SEM. Asterisks (**) refer to the p value compared with the control group. a = significant ($p < 0.0001$) compared with GBP group. * $p < 0.05$, ** $p < 0.0001$ n = 6 (number of embryos).

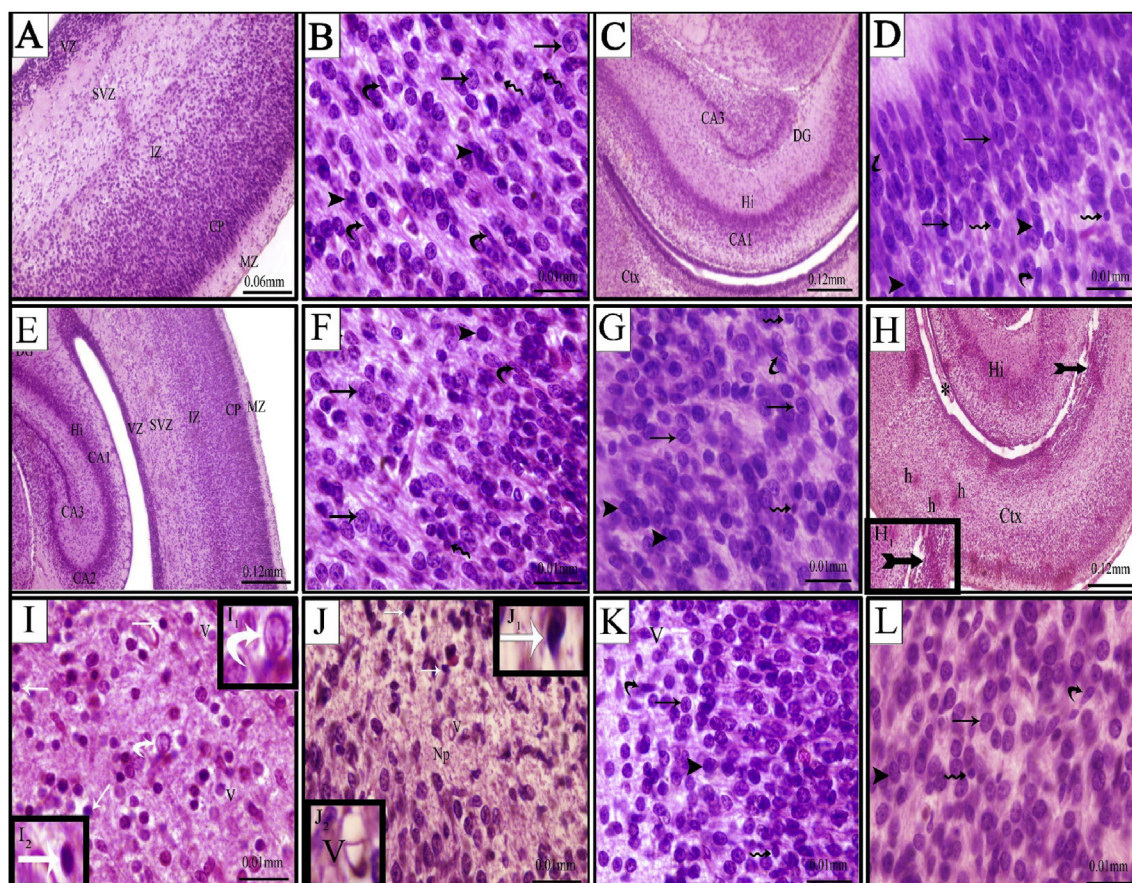


Fig. 2. Photomicrographs of cross sections passing through the cerebral cortex (A, B, E, F, H, I, K) and hippocampus (C, D, E, G, J, L) of the brain of rat fetuses from control (A–D), ginger (E–G), GBP (H–J) and GBP + ginger (K&L). A&E-the cortical layers MZ, marginal zone; CP, cortical plate; IZ, intermediate zone; SVZ, sub-ventricular zone; VZ, ventricular zone. B&F- different nerve cells in the cerebral cortex. C) the hippocampal (Hi) layers CA1, CA2, CA3 and the dentate gyrus (DG). D&G- normal arrangement of granule cells in the CA1 sub region with different nerve cells. Granule cells (arrow), pyramidal cells (arrow head), astrocytes (wavy arrow) and microglial cells (curved arrow). H- massive necrotic area (tailed arrow) with disrupted cortical layer architecture in the form of merging between the intermediate and subventricular zones as well as narrow irregular ventricle space (*). I&J-pyknotic nuclei of nerve cells (white arrow [I₂, J₁]), karyolytic nucleus (white curved arrow [I₁]), Vacuoles (V [J₂]). K&L-almost normal nerve cells and neuropil.

cytoplasm of the neurons and extended to the processes. Although most neurons were stained, the intensity varied in different neuronal populations. Bcl-2 and Caspase-3 immunoreactivity was indicated as brown color in the cytoplasm of neuronal cells in the brain sections of both cerebral cortex and hippocampus of all groups.

In the cerebral cortex, both pyramidal and granule cells stained strongly for Bcl-2, but the molecular layer, which contained sparse horizontal neurons, did not stain. Strong immunoreactivity of Bcl-2 in many neuronal cell bodies was observed in fetuses of control and ginger groups (Fig. 3A&B). Positivity of Bcl-2 expression was recorded in few scattered neurons in the cerebral cortex of brain sections after GBP injection (Fig. 3C). However, rat fetuses maternally injected with GBP + ginger revealed increased number of neuronal cells with Bcl-2 expression compared with GBP group (Fig. 3D).

The pattern of Caspase-3 immunolocalization, on the other hand, was reversible to that of the Bcl-2. Few scattered cells showed immunopositivity to Caspase-3 in the cerebral cortex of rat fetuses from control and ginger groups (Fig. 3E&F). While, almost all the cerebral cortical layers showed strong positivity for Caspase-3 immunoreaction, except in the molecular layer where few scattered cells were immuno-positive (Fig. 3G). Combined ginger and GBP group showed decreased expression of Caspase-3 antigen compared with GBP group with overall moderate immunoreaction (Fig. 3H).

In terms of the Bcl-2 immunoreaction in the hippocampus, CA1, CA3 and dentate gyrus regions were immuno-stained, including granule cells

in the dentate gyrus, and the pyramidal layer and processes from individual cells. Control and ginger groups displayed very strong reaction of Bcl-2 in the majority of hippocampal cells (Fig. 3I&J). GBP group showed severe decrease in the Bcl-2 immuno-expression with few neuronal cells expressing the antigen (Fig. 3K). On the other hand, co-administration of ginger after GBP resulted in moderate expression of Bcl-2 in the cytoplasm of neuronal cells (Fig. 3L).

Same results of cerebral cortex were obtained in the hippocampal neurons in terms of Caspase-3 expression. The control and ginger groups showed weak cytoplasmic expression (Fig. 3M&N), while the GBP group showed very strong immunoreaction in the cytoplasm of the hippocampal neurons, especially in those of the CA1 region (Fig. 3O). Moderate expression of Caspase-3 antigen was located in the hippocampal neurons when ginger was administered after GBP injection (Fig. 3P).

Fig. (4) illustrates the percentage of Bcl-2 and Caspase-3 positive cells expression in the cerebral cortex of rat fetuses. The expression of Bcl-2 was insignificantly different in ginger group compared with control group. GBP administration caused a highly significant reduction in the Bcl-2 mean area percentage expression in neuronal cells compared with the control group with only 3.12 ± 0.76 % of the cells expressing the antigen. Administration of ginger after GBP injection resulted in significant increase in percentage of Bcl-2 expression in comparison with GBP and low significant decrease when compared with control. Meanwhile, Caspase-3 immuno-expression showed insignificant difference between control and ginger groups, while it showed high significant increase in

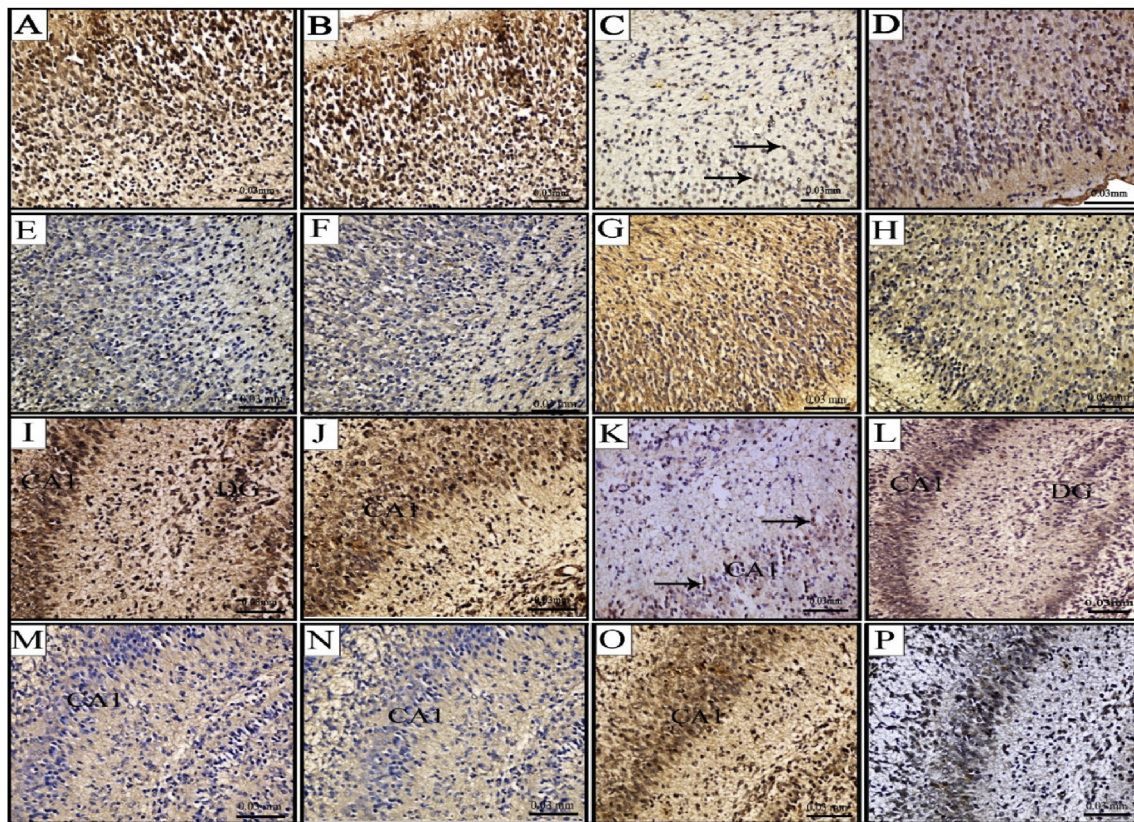


Fig. 3. Photomicrographs showing immuno-histochemical localization of Bcl-2 (A-D, I-L) and Caspase-3 (E-H, M-P) antigens in cerebral cortex (A-H) and hippocampus (I-P) of 20-day old rat fetuses. Control group (A, E, I, M), Ginger group (B, F, J, N) with increased Bcl-2 and decreased Caspase-3 expression, GBP group (C, G, K, O) with decreased Bcl-2 and increased Caspase-3 expression, GBP + ginger group (D, H, L, P) with moderate Bcl-2 and Caspase-3 expression.

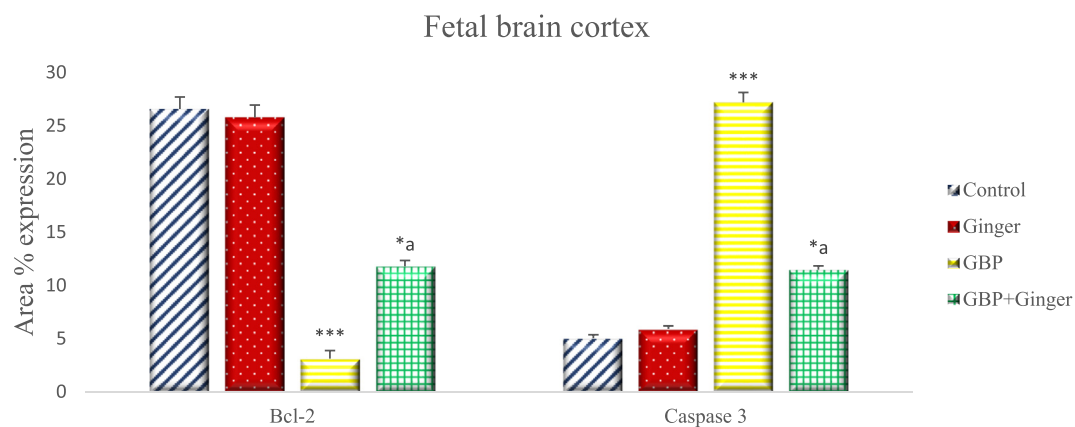


Fig. 4. Graph showing the mean area % of Bcl-2 and Caspase-3 expression in the cerebral cortex of rat fetuses of different groups. Data are represented as mean area% $\pm$ SEM. Asterisks (* - ***) refer to the p value compared with the control group. a = significant ($p < 0.05$) compared with GBP group. * $p < 0.05$, ** $p < 0.0001$ $n = 6$ (number of sections).

the GBP group compared with control group. Ginger administration resulted in significant decrease in the mean area expression when compared with GBP and low significant increase when compared with control group.

The results of the immuno-histochemical staining of the hippocampus of rat fetuses revealed similar results to that of the cerebral cortex (Fig. 5). The mean area percentage of Bcl-2 positive cells in the control and ginger groups were significantly higher than those of the GBP group. Furthermore, the mean area percentage of Bcl-2 positive cells in the combined ginger and GBP injected groups were significantly higher than those of the GBP group only. Conversely, the mean area percentage of

cells positive for Caspase-3 showed high significant increase in the GBP group, compared with those of the control group or those of the ginger administered group which had low expression levels. Co-administration of ginger after GBP injection resulted in significant reduction in the mean area percentage of Caspase-3 positive cells, compared with that of the GBP group.

3.4. Ultrastructural investigation

The cerebral cortex did not demonstrate substantial differences among rats in control and ginger groups and it was similar to the well-

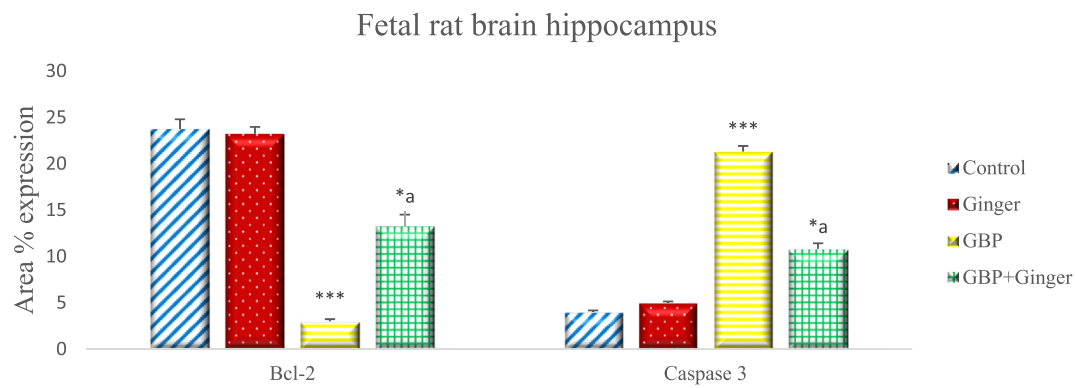


Fig. 5. Graph showing the mean area % of Bcl-2 and Caspase-3 expression in the hippocampus of rat fetus of different groups. Data are represented as mean area% $\pm$ SEM. Asterisks (* - **) refer to the p value compared with the control group. a = significant ($p < 0.05$) compared with GBP group. * $p < 0.05$, ** $p < 0.0001$ $n = 6$ (number of sections).

known normal ultrastructural picture. The ultrastructure of the dorsal cerebral cortical brain cells in rat fetuses from the control group exhibited clear neuronal structures. The fine picture of neural tissue revealed intact neurons with well-defined smooth nuclear membrane.

The neurons had clear cell membranes, normal cytoplasmic density and large, round euchromatic nuclei with evenly distributed chromatin and prominent nucleoli. Numerous organelles were concentrically arranged around the nucleus. The cytoplasmic area contained plenty of rER which

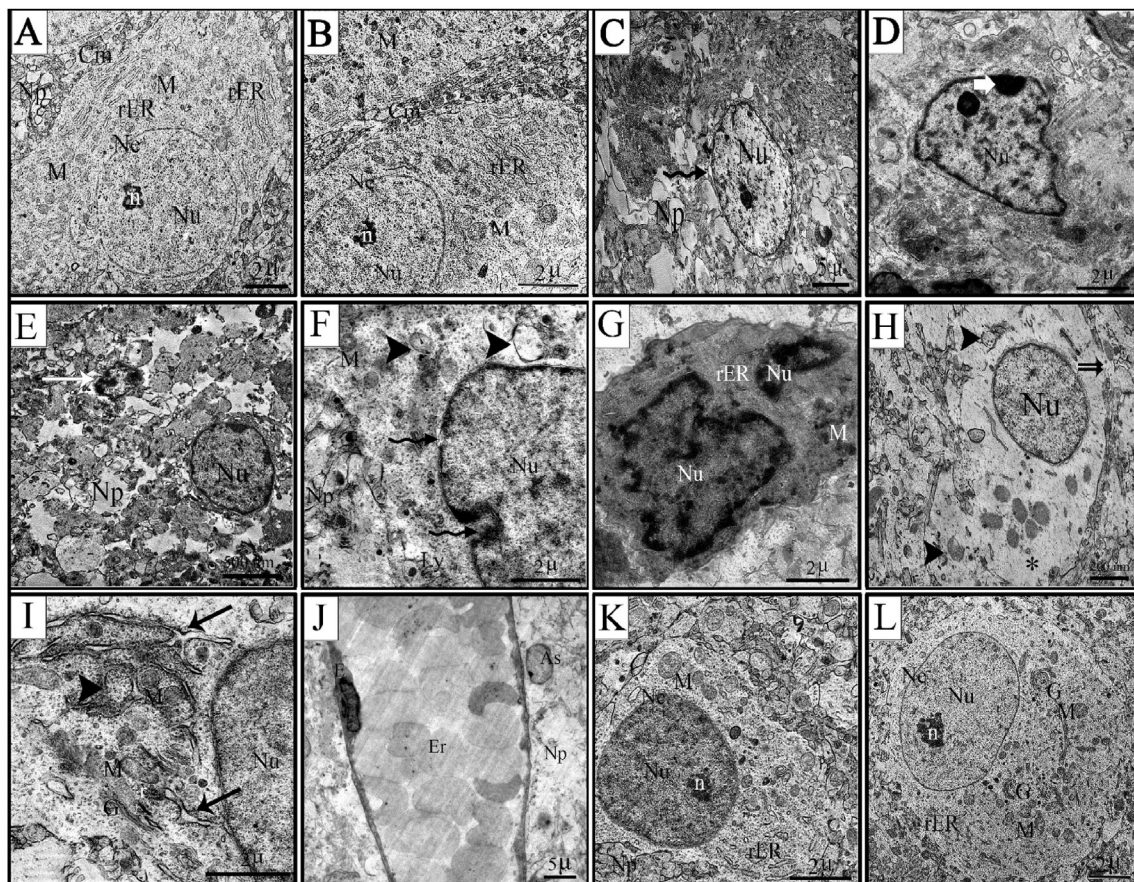


Fig. 6. Transmission electron photomicrographs of cerebral cortex sections of rat fetuses. (A) Control group (B) Ginger group (C–J) GBP group (K&L) GBP + ginger group. A&B- perikaryons of normal nerve cell containing euchromatic nucleus (Nu) with normal nuclear envelope (Ne), and prominent nucleolus (n), normal cytoplasm containing (rER) and mitochondria (M) as well as intact cell membrane (Cm). Normal neuropil without any signs of edema (Np). C- chromatolytic nuclei (Nu) with abnormal nuclear envelop (wavy arrow) and swollen neuropil (Np). D-abnormal nuclei (Nu) with chromatin clumping below the nuclear membrane (white arrow). E-shrunk nucleus (arrow) surrounded by vacuolated neuropil (Np). F- indentation and discontinuity in the nuclear envelope (wavy arrow) accompanied by swollen mitochondria (M) with partial or total loss of cristae (arrow head) and swollen neuropil (Np), in addition to increased number of lysosomes (Ly). G-apoptotic cell with degenerated nucleus (Nu) and very electron dense cytoplasm. H- rarefied cytoplasm (*) with few scattered mitochondria, some of which were ruptured (arrow head). The discontinuity in the cell membrane was evident (double arrow). I- dilated and fragmented rER with partial loss of the attached ribosomes (arrow), swollen mitochondria with partial loss of cristae (arrow head). J-enlarged and dilated brain capillary with obvious congestion (Er). K&L-nerve cells with normal appearing nuclei (Nu) and prominent nucleoli (n). Normal cytoplasm containing mitochondria (M) and Golgi (G), although the rER appeared fragmented. Surrounding neuropil is similar to that of the control nerve cells (Np).

were arranged in stacks parallel to each other. Abundant spherical and elongated mitochondria with well-preserved cristae were observed. The surrounding neuropil appeared normal with no signs of edema or vacuolation (Fig. 6A&B).

Cortical neurons of rat fetuses maternally injected with GBP during the organogenesis phase exhibited degenerative changes at the nuclear, cytoplasmic and cell membrane levels. Regarding the nuclear changes, two major nuclear degenerative features were evident, namely chromatolysis or pyknosis. The chromatolytic neurons were enlarged compared with the control neurons (Fig. 6C). The chromatin particles were unevenly distributed and often formed clumps beneath the nuclear membrane (Fig. 6D). The second type of nuclear changes was pyknotic neurons. These neurons were dark irregular shape, with very electron-dense cytoplasm. This was evidenced by decrease in the nuclear diameter as shown in Table (1) compared with neural cells of the control group (4.7 ± 0.052 ; 7.20 ± 0.073 for GBP and control group, respectively). The nuclei and organelles of these neurons were poorly defined, small, and had irregular outlines (Fig. 6E&G). Some neuronal cells showed shrunken irregular nuclei (Fig. 6E). The nuclear membrane was irregular with prominent enfolding and indentations (Fig. 6C-G). Also, disappearance of some parts of the nuclear membrane was clearly detected as well as widened nuclear membrane space (Fig. 6C&F).

The cerebral cortex showed evident neuronal cytoplasmic swelling in the form of loose, empty and bright cytoplasm as well as swollen and/or degenerated organelles, especially rER and mitochondria. Neuron cytoplasm of the GBP group contained areas of low electron density and appeared rarefied with unevenly distributed cellular organelles accompanied by a ruptured and discontinuous cell membrane (Fig. 6H). Mitochondrial swelling, crista rupture or vacuolar degeneration were visible with missing of their internal compartments. Some cells had severely damaged mitochondria with loss of nearly all cristae (Fig. 6F, H, I). The cytoplasm showed dilatation of the rER cisternae as well as loss of ribosomes (Fig. 6I). Disruption of whole synaptic structures resulting in swollen and degenerated neuropil was evident (Fig. 6 C, E, F).

Congested and dilated blood vessel with red blood cells could be observed. The endothelial cytoplasm was also highly electron dense and contained pyknotic nuclei accompanied by astroglial edema. Moreover, the matrix around the capillaries appeared swollen (Fig. 6J).

The cerebral cortex of fetuses maternally injected with GBP followed by ginger showed ameliorated ultrastructure in the perikaryon and neuropil compared with those of the GBP group. The neurons were clearly observed with euchromatic nucleus, including very active nucleoli and, to some extent, regular nuclear envelope. The subcellular organelles, especially mitochondria, rER and Golgi complex showed normal ultrastructure. In general, the structural damage in the cerebral cortex was less prominent than that of the GBP group (Fig. 6K&L). Additionally, the nuclear diameter significantly increased compared with the GBP group (Table 1; 6.48 ± 0.114).

4. Discussion

Exposure to AEDs during a critical period in nervous system development causes long-term detrimental effects on the neural development

(Kim et al., 2007). Various AEDs were found to induce neural tube defects in different animal models (Özer et al., 2012; Ozgural et al., 2015). The strongest evidence for drugs causing neural tube defects exists for valproic acid and carbamazepine (Mitchell et al., 2004). GBP, like the other AEDs had been reported to affect neural tube development, or induce neural tube defects (Afshar and Gholipour, 2008). The reduction in the fetal brain weight in the GBP group was evident in the present study. Similar results were observed in the study of Prakash et al. (2008) who found that GBP exposure resulted in decrease in size and malformation in shape in the brains of mice fetuses. Similarly, prenatal administration of phenytoin in rodents resulted in a reduction in brain weight (Ogura et al., 2002).

The present study investigated the effect of GBP administration in two areas of the brain, namely the cerebral cortex and the hippocampus. The cerebral cortex is most specifically responsible for consciousness with essential role in recognition, memory, thoughts, mental capability and intelligence (Eluwa et al., 2008). In addition, several observations suggest that cortical malformations involving the hippocampus are instrumental in mental retardation (Barkovich and Raybaud, 2004). Furthermore, it has been established that the hippocampus in the brain may be most vulnerable to the neurotoxicity of neurotoxic materials in the very rapid growth period (Liu et al., 2003).

Histologically, the current study showed that injection of GBP induced various histological alterations in both the cortical and hippocampal regions of the brain. These results were consistent with Prakash et al. (2008) who found that administration of GBP resulted in vacuolization and cavity formation in the brain tissue. Singh and Mishra (2005) and Mohanty et al. (2011) reported that in utero administration of topiramate and lamotrigine induced hippocampal and cortical malformations in a dose dependent manner.

Two factors have been considered to be responsible for the loss in the cellularity in the present study: (1) a decrease in proliferation of brain cells and (2) induction of cell death in the brain cells of drug treated embryos (Doshi et al., 2015). It has been postulated that one of the mechanisms causing appearance of side effects of AEDs is neuronal apoptosis during late gestational and prenatal period. The present study showed downregulation and decreased expression of the anti-apoptotic marker Bcl-2 and upregulation and increase in the expression of proapoptotic marker Caspase-3 in the brain of fetuses in the GBP group, indicative of neuronal cell death. This was consistent with the study of Han et al. (2015) who found that administration of different dosages of phenobarbital resulted in decreased number of Bcl-2 positive cells and increased number of cells positive for Bax in the brain of rats compared with those of the control group. Intragastric administration of phenytoin in epileptic mice resulted in increased expression of Caspase-3 in both the hippocampal and cortical region (Zhang et al., 2015).

Electron microscopy investigation showed that the neuronal cells were degenerated under the effect of GBP injection either on the nuclear or cytoplasmic levels. Similar results were found in the study of Shalaby and Sarhan (2008) where the ultrastructure of the cerebellum of valproic acid administered rats showed degenerative features. Moreover, electron microscopy revealed that the cells degenerating in the brains of phenytoin-treated rats displayed ultrastructural changes similar to those described in neurons undergoing programmed cell death (Ikonomidou and Turski, 2009).

The appearance of dark neurons was evident in the fetal brain which could reflect a certain phase of apoptosis (Upachit et al., 2015). The mitochondria in the current study showed various forms of degeneration. Growing evidence shows that mitochondrial dysfunction is an important factor in a cascade of neurotoxic events (Ekinci et al., 2014; Afifi and Embaby, 2016). The rER dilatation may be due to lipid peroxidation (Yan et al., 2012). Disruption of the cell membrane of the neuronal cells was attributed by Mitchell et al. (2006) to dissociation of the cytoskeletal elements which could result in detachment of the cell membrane, rendering it susceptible to stretch and rupture.

The exact mechanism of the teratogenic effects of GBP on the brain is

Table 1
The nuclear diameter (μm) of the neural cells of the cerebral cortex of fetuses from different groups.

Groups	Control	Ginger	GBP	GBP + Ginger
Mean $\pm$ SEM	7.20 ± 0.073	7.07 ± 0.067	$4.7 \pm 0.052^{**}$	$6.48 \pm 0.114^{**a}$

Data are represented as mean area% $\pm$ SEM.

Asterisks (* - **) refer to the p value compared with the control group.

a = significant ($p < 0.05$) compared with GBP group.

* $p < 0.05$, ** $p < 0.0001$ n = 6 (nerve cells).

not clear (Afshar and Gopalipour, 2008). However, animal studies propose a few conceivable mechanisms of different AEDs including altered neuronal proliferation and migration, synaptogenesis, and apoptosis. Each of these processes is vital for normal neural development. The mechanism of action of AEDs affects mainly neurotransmitter systems. NMDA receptors is the primary excitatory influence on neuronal activity and cell proliferation, whereas GABA has strong inhibitory influence. In animal studies, blockade of NMDA receptors or enhanced GABA inhibition impairs neurogenesis and cell migration (Stefovska et al., 2008), bringing about diminished brain volume and cortical dysplasia. The other possible mechanisms include induction of apoptosis, especially in neural tube cells, and production of the free radicals such as epoxide during metabolism of GBP (Pippenger, 2003). AEDs were also found to hinder the endogenous neuroprotective system in the brain that is crucial for neuronal survival during development (Huang and Reichardt, 2001). An important factor controlling the susceptibility of brain to AEDs is the timing of exposure. It has been reported that administration of teratogens from GD 7 to GD 13, the most critical period of gestation, induced reduction in cell population, reduction in thickness in some zones, disappearance of intermediate zone and disruption of the marginal zone in the cerebral cortex (Eluwa et al., 2008).

In the last few years, greater attention has been given to the curative potentials of medicinal plants as natural antioxidants, due to their lack of side effects and low cost (Saleh et al., 2018). Ginger has extensively been reported to have potential antioxidant properties, which might be related to the shogaols, gingerols, and other phenolic-ketone derivatives shown to be beneficial in alleviating ROS-induced CNS damage (Shanmugam et al., 2011; Hussein et al., 2017).

The present study showed improvements in the fetal brain weight after co-administration of ginger with GBP. As an evidence on the ameliorating effect of ginger in brain, Hashish (2014) found that combined insulin–ginger treatment showed significant increase in cerebellar weight as compared with the diabetic rats. Moreover, combined treatment of ginger and GBP in the present study revealed its neuroprotective effect evidenced by overall enhancement in the investigated brain tissues in the fetuses with peculiar arrangement of different cortical cell layers, decreased expression of caspase-3 and increased expression of Bcl-2, in addition to improved ultrastructure. This was consistent with the study of El-Tantawi (2007) who concluded that ginger may protect the nervous tissue of the spinal cord and cerebellum or at least decreases the damaging effects of acrylamide on CNS tissues. Shati and Elsaid (2009) studied the effect of water extracts of thyme and ginger on alcohol abuse and reported significant amelioration of the alcohol induced changes in the brain tissue. Waggas (2009) also found that ginger could minimize the neuro chemical damage of the brain areas under the effect of monosodium glutamate. Ginger administration has also shown neuroprotective effect in diabetic rats where it dramatically reduced the number of Caspase-3 positive cells (Li et al., 2012; El-Akabawy and El-Kholy, 2014). Moreover, ethanolic extract of ginger was found to protect the brain of rats from the deleterious effects of huntington disease indicated by reduction in inflammation, necrosis and gliosis (Sharma et al., 2012). Ginger also has been reported to ameliorate the effect of Alzheimer's disease (Mahdy et al., 2014). Also, significant decrease in the brain level of Caspase-3 in Alzheimer's-induced rats was evident after administration of ginger extract or ginger oil (Ahmed et al., 2014).

The neuroprotective effect of ginger may be attributed to different mechanisms. Shukla and Singh (2007) showed that the neuroprotective effects of ginger extract may be mediated through free radical scavenging activity, inhibition of cholinesterase, and pro-inflammatory cytokines. Ginger aqueous extract has been reported to increase the function of cholinergic neuron, inhibit Acetyl cholinesterase activity and increase the ratio of super oxide dismutase/malondialdehyde as well as decrease the malondialdehyde content in brain (Joshi and Parle, 2006; Wang et al., 2008; Sharma et al., 2012). Also, it has been postulated that the neuroprotective effect of ginger extract might be related to its antioxidant effect (Wattanathorn et al., 2011). Shogaols, and zingerone in ginger

have shown various pharmacological activities including antioxidant activity so that, they can scavenge free radicals, inhibit the secretion of cytokines and suppress the cell death. The ability to control ROS is thus crucial in neurodegenerative diseases, because neuronal damage occurs when the "oxidant– antioxidant" balance is disturbed in favor of excess oxidative stress. ROS-scavengers effectively protect neurons against both necrotic and apoptotic cell death (Dong et al., 2009). In addition, the administration of ginger has been shown to improve oxidative stress by decreasing lipid peroxidation and protein oxidation as free radical generating sources and elevating the levels of enzymes implicated in the antioxidant defense system (Abd-Allah and Sharaf El-Din, 2013).

5. Conclusion

In the light of, histological, immuno-histochemical and ultrastructural results, the present data confirmed that GBP has adverse effects on the brain of rat fetuses and induced neurodegenerative, apoptosis and altered ultrastructure in the cerebral cortical and hippocampal regions. Furthermore, ginger might be a potential candidate agent against experimentally induced GBP induced toxicity via its antioxidant and free radical-scavenging properties. Therefore, it is recommended to take ginger in parallel with GBP during pregnancy for better fetal brain development.

Declarations

Author contribution statement

Gamal M Badawy: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Marwa N Atallah: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Saber A Sakr: Contributed reagents, materials, analysis tools or data.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

- Abd-El-Aty, O., Morgan, E., 2011. Ginger administration has a protective effect on the liver of albino rats treated with 6-mercaptopurine drug. *J. Am. Sci.* 7, 737–745.
- Abd-Allah, O., Sharaf El-Din, A., 2013. The possible protective effect of ginger against intestinal damage induced by methotrexate in rats. *Med. J. Cairo Univ.* 81, 1073–1084.
- Afifi, O., Embaby, A., 2016. Histological study on the protective role of ascorbic acid on cadmium induced cerebral cortical neurotoxicity in adult male albino rats. *J. Microsc. Ultra.* 4, 36–45.
- Afshar, M., Gopalipour, M., 2008. Teratogenic effects of gabapentin on neural tube and limb development in mice. *Neurosciences* 13, 321–323.
- Ahmed, H., Zaazaa, A., Abd El-Motelp, B., 2014. *Zingiber officinale* and Alzheimer's disease: evidences and mechanisms. *Int. J. Pharm. Sci. Rev. Res.* 27, 142–152.
- Badawy, G., Atallah, M., Sakr, S., 2019. The ameliorative role of ginger administration against gabapentin-induced hepatotoxicity in rat fetuses. *EJPMR* 6, 622–631.
- Ban, L., Fleming, K., Doyle, P., Smeeth, L., Hubbard, R., Fiaschi, L., Tata, L., 2015. Congenital anomalies in children of mothers taking antiepileptic drugs with and without Periconceptional high dose folic acid use: a population-based cohort study. *PLoS One* 10, e0131130.
- Barkovich, A., Raybaud, C., 2004. Neuroimaging in disorders of cortical development. *Neuroimaging Clin. N. Am.* 14, 231–254.

- Bittigau, P., Siffringer, M., Genz, K., Reith, E., Pospischil, D., Govindarajulu, S., Dziatko, M., Pesditschek, S., Mai, I., Dikranian, K., Olney, J., Ikonomidou, C., 2002. Antiepileptic drugs and apoptotic neurodegeneration in the developing brain. *Proc. Natl. Acad. Sci. U.S.A.* 99, 15089–15094.
- Dong, X., Wang, Y., Qin, Z., 2009. Molecular mechanisms of excitotoxicity and their relevance to pathogenesis of neurodegenerative diseases. *Acta Pharmacol. Sin.* 30, 379–387.
- Doshi, M., Sultana, S., Jayasree, N., Jyothi, A., Chandrupatla, M., 2015. Effect of sodium valproate on neural tube development in chick embryos. *IJRPP* 4, 15–18.
- Ekinci, C., Tahaoglu, A., Yavuz, D., Deveci, E., Aktas, A., Yilmaz, T., Yumusak, Ö., Yükselmis, O., 2014. Ultrastructural effects of the propineb on brain of fetuses during rat pregnancy. *Int. J. Morphol.* 32, 1467–1471.
- El-Akabay, G., El-Kholy, W., 2014. Neuroprotective effect of ginger in the brain of streptozotocin-induced diabetic rats. *Ann. Anat.* 196, 119–128.
- El-Tantawi, H., 2007. The protective role of ginger (*Zingiber officinale*) against acrylamide induced neurotoxicity in mice. *Egypt J. Histol.* 30, 325–336.
- Eluwa, M., Njoku, C., Ekanem, T., Akpantah, A., 2008. Teratogenic effect of beer and palm wine on histology of fetal cerebral cortex of Wistar rats. *Int. J. Health* 9.
- Ferri, M., Mayor, P., López-Fraile, P., Siquier, E., Moro, M., Berdusan, F., 2018. Comparative study of antiepileptic drug use during pregnancy over a period of 12 years in Spain. Efficacy of the newer antiepileptic drugs lamotrigine, levetiracetam, and oxcarbazepine. *Neurologia* 33, 78–84.
- Fisher, R., Boas, W., Blume, W., Elger, C., Genton, P., Lee, P., Engel, J., 2005. Epileptic seizures and epilepsy: definitions proposed by the international league against epilepsy (ILAE) and the International Bureau for Epilepsy (IBE). *Epilepsia* 46, 470–472.
- Fujii, H., Goel, A., Bernard, N., Pistelli, N., Yates, L., Stephens, S., Han, J., Matsui, D., Etwell, F., Einarson, T., Koren, G., Einarson, A., 2013. Pregnancy outcomes following gabapentin use. Results of a prospective comparative cohort study. *Neurology* 80, 1565–1570.
- Gilboa, S., Broussard, C., Devine, O., Duwe, K., Flak, A., Boulet, S., Moore, C., Werler, M., Honein, M., 2011. Influencing clinical practice regarding the use of antiepileptic medications during pregnancy: modeling the potential impact on the prevalences of spina bifida and cleft palate in the United States. *Am. J. Med. Genet. C. Sem. Med. Genet.* 157C, 234–246.
- Glauser, T., Ben-Menachem, E., Burgeois, B., Cnaan, A., Guerreiro, C., Kälviäinen, R., Mattson, R., French, J., Perucca, E., Tomson, T., 2013. ILAE Subcommittee on AED Guidelines. Updated ILAE evidence review of antiepileptic drug efficacy and effectiveness as initial monotherapy for epileptic seizures and syndromes. *Epilepsia* 54 (3), 551–563.
- Halvorsen, K., Landmark, C., Granas, A., 2016. Prevalence of different combinations of antiepileptic drugs and CNS drugs in elderly home care service and nursing home patients in Norway. *Epilep. Res. Treat* 2016.
- Han, B., Fu, P., Ye, Y., Zhang, H., Wang, G., 2015. Protective effects of tetrandrine on brain cells in phenobarbital-dependent and -withdrawn rats. *Mol. Med. Rep.* 11, 1939–1944.
- Hashish, H., 2014. Alteration of glial fibrillary acidic protein immunoreactivity in astrocytes of the cerebellum of diabetic rats and potential effect of insulin and ginger. *Anat. Physiol.* 5, 167.
- Huang, E., Reichardt, L., 2001. Neurotrophins: roles in neuronal development and function. *Annu. Rev. Neurosci.* 24, 677–36.
- Hussein, A., Ahmed, O., 2010. Regioselective one-pot synthesis and antiproliferative and apoptotic effects of some novel tetrazolo[1,5-a] pyrimidine derivatives. *Bioorg. Med. Chem.* 18, 2639–2644.
- Hussein, U., Hassan, N., Elhalwagy, M., Zaki, A., Abubakr, H., Venkata, K., Jang, K., Bishayee, A., 2017. Ginger and propolis exert neuroprotective effects against monosodium glutamate-induced neurotoxicity in rats. *Molecules* 22, 1928.
- Ikonomidou, C., Turski, L., 2009. Antiepileptic drugs and brain development. *Epilepsy Res.* 88, 11–22.
- Johari, H., Delimasab, F., Sharifi, E., Hemayat-Khah, V., Pourdanesh, M., Kargar, H., Nikpour, M., Yazdani, M., 2013. The effects of hydro-alcoholic extract of *Zingiber officinale* on prevention from plumbism in kidney tissue of neonatal rats. *ZJRMS* 15, 13–17.
- Joshi, H., Parle, M., 2006. *Zingiber Officinale*: evaluation of its nootropic effect in mice. *Afr. J. Trad. S.* 3, 64–4.
- Kim, J., Kondratyev, A., Gale, K., 2007. Antiepileptic drug-induced neuronal cell death in the immature brain: effects of carbamazepine, topiramate, and levetiracetam as monotherapy versus polytherapy. *JPET* 323, 165–173.
- Li, Y., Tran, V., Duke, C., Roufogalis, B., 2012. Preventive and protective properties of *Zingiber officinale* (ginger) in diabetes mellitus, diabetic complications, and associated lipid and other metabolic disorders: a brief review. *Evid. Based Complement Alternat. Med.* 1–10.
- Liu, R., Liu, I., Bi, X., Thompson, R., Doctrow, S., Malfroy, B., Baudry, M., 2003. Reversal of age-related learning deficits and brain oxidative stress in mice with superoxide dismutase/catalase mimetics. *Proc. Natl. Acad. Sci. USA* 100, 8526–8531.
- Macfarlane, A., Greenhalgh, T., 2018. Sodium valproate in pregnancy: what are the risks and should we use a shared decision-making approach? *BMC Pregnancy Childbirth* 18, 200.
- Mahdy, K., Gouda, N., Abd El-Fattah, M., Yassin, N., El-Shenawy, S., Abdel Razik, F., Ibrahim, B., 2014. A3Protective Effect of ginger (*Zingiber officinale*) on Alzheimer's disease induced in rats. *J. Neuroinfect. Dis.* 5, 159.
- Meador, J., Baker, G., Finnell, R., Kalayjian, L., Liporace, J., Loring, D., Mawer, G., Pennell, P., Smith, J., Wolff, M., 2006. In utero antiepileptic drug exposure: fetal death and malformations. *Neurology* 67, 407–412.
- Mitchell, L., Adzick, N., Melchionne, J., Pasquariello, P., Sutton, L., Whitehead, A., 2004. Spina bifida. *Lancet* 364, 1885–1895.
- Mitchell, R., Kumar, V., Abbas, A., Fausto, N., 2006. Pocket Companion to Robbins and Cotran Pathologic Basis of Disease, seventh ed. Saunders.
- Mohanty, C., Shah, N., Dhungel, S., Das, B., 2011. Effect of lamotrigine on fetal rat brain. *People's J. Sci. Res.* 4, 5–7.
- Nanjundaiah, S., Annaiah, H., Dharmesh, S., 2011. Gastroprotective effect of ginger rhizome (*Zingiber officinale*) extract: role of gallic acid and cinnamic acid in H⁺, K⁺—ATPase/H. pylori inhibition and anti-oxidative mechanism. *Evid. Based Complement Alternat. Med.* 1–13.
- Ogura, H., Yasuda, M., NaKamura, S., 2002. Neurotoxic damage of granule cells in the dentate gyrus and the cerebellum and cognitive deficit following neonatal administration of phenytoin in mice. *J. Neuropathol. Exp. Neurol.* 61, 956–967.
- Olney, J., Young, C., Wozniak, D., Jevtic-Todorovic, V., Ikonomidou, C., 2004. Do pediatric drugs cause developing neurons to commit suicide? *Trends Pharmacol. Sci.* 25, 135–139.
- Özer, F., Demirel, A., Dilsiz, Ö., Aydın, M., Özdemir, N., Uyanıkgil, Y., Baka, M., 2012. Effects of levetiracetam on neural tube development and closure of the chick embryos *in ovo*. *Childs. Nerv. Syst.* 28, 969–976.
- Ozgural, O., Armanan, E., Bozkurt, M., Eroglu, U., Kahilogullari, G., Unlu, A., 2015. The effect of levetiracetam on closure of the midline in early chicken embryos. *Turk. Neurosurg.* 25, 681–684.
- Padmanabhan, R., Abdurazzaq, Y., Bastaki, S., Shafiullah, M., 2008. Intrauterine growth restriction and skeletal variations in mouse fetuses induced by vigabatrin administered at preimplantation stages of development. *Congenital. Anom.* 48, 29–39.
- Page, G., Barnes, J., 1964. Toxicity tests. In: Laurence, D., Bacharach, A. (Eds.), *Evaluation of drug activities pharmaceuticals*. Academic Press 1, London and New York, pp. 160–162.
- Pippenger, C., 2003. Pharmacology of neural tube defects. *Epilepsia* 44, 24–32.
- Prakash, Prabhu, L., Rai, R., Pai, M., Yadav, S., Madhyastha, S., Goel, R., Singh, G., Nasar, M., 2008. Teratogenic effects of the anticonvulsant gabapentin in mice. *Singap. Med. J.* 49, 47–53.
- Saleh, H., Abd El-Aziz, G., Mustafa, H., El-Fark, M., Tashkandi, J., Alzahrani, A., Mal, A., Aburas, M., Salem, A., 2018. Beneficial effects of curcumin in maternal and fetal oxidative stress and brain damage induced by gestational lead administration. *Biomed. Pharmacol. J.* 11, 871–887.
- Schindelin, J., Arganda-Carreras, I., Frise, E., Kaynig, V., Longair, M., Pietzsch, T., Preibisch, S., Rueden, C., Saalfeld, S., Schmid, B., Tinevez, J.Y., White, D.J., Hartenstein, V., Eliceiri, K., Tomancak, P., Cardona, A., 2012. Fiji: an open-source platform for biological-image analysis. *Nat. Methods* 9, 676–682.
- Shalaby, N., Sarhan, N., 2008. Light and electron microscopic study on the effect of valproic acid on cerebellar cortex of adult male albino rats and the possible protective effect of L-carnitine. *Egypt J. Histol.* 31, 256–265.
- Shanmugam, K., Mallikarjuna, K., Kesireddy, N., Reddy, K., 2011. Neuroprotective effect of ginger on antioxidant enzymes in streptozotocin-induced diabetic rats. *Food Chem. Toxicol.* 49, 893–897.
- Sharma, M., Sharma, N., Sharma, R., 2012. Neuroprotective effect of *Zingiber officinale* in 3-np-induced huntington disease. *J. Pharm. (Lahore)* 2, 277–289.
- Shati, A., Elsaid, F., 2009. Effects of water extracts of thyme (*Thymus vulgaris*) and ginger (*Zingiber officinale* Roscoe) on alcohol abuse. *Food Chem. Toxicol.* 47, 1945–1949.
- Shukla, Y., Singh, M., 2007. Cancer preventive properties of ginger: a brief review. *Food Chem. Toxicol.* 45, 683–690.
- Singh, M., Mishra, A., 2005. Prenatal topiramate exposure induced developmental changes in rat brain. *Ann. Neurosci.* 12, 16–18.
- Soysal, H., Unur, E., Düzler, A., Karaca, O., Ekinci, N., 2011. Effects of intraperitoneal administration of the phenytoin on the skeletal system of rat fetus. *Seizure* 20, 187–193.
- Stefovska, V., Uckermann, O., Czuczwar, M., Smitka, M., Czuczwar, P., Kis, J., Kaendl, A., Turski, L., Turski, W., Ikonomidou, C., 2008. Sedative and anticonvulsant drugs suppress postnatal neurogenesis. *Ann. Neurol.* 64, 434–445.
- Sternberger, L., 2006. *Immunocytochemistry*, 3rd ed. John Wiley Medical, New York, pp. 190–209.
- Sveberg, L., Svalheima, S., Taubøllab, E., 2015. The impact of seizures on pregnancy and delivery. *Seizure* 28, 35–38.
- Upachit, T., Lanlua, P., Sricharoenvej, S., 2015. Ultrastructural changes in the neuronal superior colliculus in the early stage of streptozotocin-induced diabetes mellitus in rats. *Sci. Res. Essays* 10, 114–119.
- Verrotti, A., Scaparrotta, A., Cofini, M., Chiarelli, F., Tiboni, G., 2014. Developmental neurotoxicity and anticonvulsant drugs: a possible link. *Reprod. Toxicol.* 48, 72–80.
- Waggas, A., 2009. Neuroprotective Evaluation of extract of ginger (*Zingiber officinale*) root in monosodium glutamate-induced toxicity in different brain areas male albino rats. *Pak. J. Biol. Sci.* 12, 201–212.
- Wang, J., Hang, Q., Jia, S., 2008. Effect of aqueous extract of ginger on vascular dementia in rats. *J. Media Res.* 8.
- Wattanathorn, J., Jittiwat, J., Tongun, T., Muchimapura, S., Ingkaninan, K., 2011. *Zingiber officinale* mitigates brain damage and improves memory impairment in focal cerebral ischemic rat. *Evid. Based Complement Alternat. Med.* 429–505.
- Yan, Y., Bian, J., Zhong, L., Zhang, Y., Sun, Y., Liu, Z., 2012. Oxidative stress and apoptotic changes of rat cerebral cortical neurons exposed to cadmium *in vitro*. *Biomed. Environ. Sci.* 25, 172–181.
- Zahedi, A., Fathiadzad, F., Khaki, A., Ahmadian, B., 2012. Protective effect of ginger on gentamicin-induced apoptosis in testis of rats. *Adv. Pharmacol. Bull.* 2, 197–200.
- Zhang, C., Fan, Q., Chen, S., Kaohsiung, H., 2015. Reversal of P-glycoprotein overexpression by *Ginkgo biloba* extract in the brains of pentylenetetrazole-kindled and phenytoin-treated mice. *J. Med. Sci.* 31, 398–404.