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Impaired neurotransmission in ether lipid-deficient nerve terminals

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Isolated defects of ether lipid (EL) biosynthesis in humans cause rhizomelic chondrodysplasia punctata type 2 and type 3, serious peroxisomal disorders. Using a previously described mouse model [Rodemer, C., Thai, T.P., Brugger, B., Kaercher, T., Werner, H., Nave, K.A., Wieland, F., Gorgas, K., and Just, W.W. (2003) Inactivation of ether lipid biosynthesis causes male infertility, defects in eye development and optic nerve hypoplasia in mice. *Hum. Mol. Genet.*, 12, 1881–1895], we investigated the effect of EL deficiency in isolated murine nerve terminals (synaptosomes) on the pre-synaptic release of the neurotransmitters (NTs) glutamate and acetylcholine. Both Ca^{2+}-dependent exocytosis and Ca^{2+}-independent efflux of the transmitters were affected. EL-deficient synaptosomes respire at a reduced rate and exhibit a lowered adenosin-5′-triphosphate/adenosine diphosphate (ATP/ADP) ratio. Consequently, ATP-driven processes, such as synaptic vesicle cycling and maintenance of Na^+, K^+ and Ca^{2+} homeostasis, might be disturbed. Analyzing reactive oxygen species in EL-deficient neural and non-neural tissues revealed that plasmalogens (PLs), the most abundant EL species in mammalian central nervous system, considerably contribute to the generation of the lipid peroxidation product malondialdehyde. Although EL-deficient tissue contains less lipid peroxidation products, fibroblasts lacking ELs are more susceptible to induced oxidative stress. In summary, these results suggest that due to the reduced energy state of EL-deficient tissue, the Ca^{2+}-independent efflux of NTs increases while the Ca^{2+}-dependent release declines. Furthermore, lack of PLs is mainly compensated for by an increase in the concentration of phosphatidylethanolamine and results in a significantly lowered level of lipid peroxidation products in the brain cortex and cerebellum.

INTRODUCTION

The role ether lipids (ELs) play in cellular physiology is still enigmatic. Cells deficient in the peroxisomal enzymes dihydroxyacetonephosphate acyltransferase (DAPAT) or alkyl dihydroxyacetonephosphate synthase lack ELs including plasmalogens (PLs) (1,2). Although viable, these cells exhibit morphological alterations of the endoplasmic reticulum (ER), Golgi apparatus, caveolae and coated pits and show defects in endocytosis and intracellular distribution of cholesterol. To further explore previously unknown EL functions, we generated an EL-deficient mouse model by targeted deletion of DAPAT (3,4). EL-deficient mice show severe phenotypes including development of cataract, various abnormalities of the central nervous system (CNS) (5) and arrest of spermatogenesis (6), changes that are reminiscent of rhizomelic chondrodysplasia punctata (RCDP) types 2 and 3, human peroxisomal disorders distinguished by isolated genetic defects in EL biosynthesis (7,8). Patients with severe RCDP show magnetic resonance imaging abnormalities the severity of which correlates with the clinical appearance and the level of PLs (7–9). Both RCDP patients and mice with targeted deletion of the DAPAT gene share phenotypes, such as growth retardation, bilateral cataract, motor impairment and defects in myelination (4,5), suggesting these mice to be a useful model system of RCDP.

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The defects studied in the cerebellum revealed axonal swellings distinguished by disorganization of septate-like junctions and accumulations of inositol-tris-phosphate receptor-containing ER-like cisternae frequently located close to the nodes of Ranvier. Moreover, patterning of climbing and parallel fibers was severely disturbed, indicating imbalance of the activities of GluRδ2-dependent and voltage-dependent Ca^{2+} channel α1A-dependent synapses (5). Thus, impaired synaptic activities may well contribute to the structural alterations caused by EL deficiency.

In presynaptic nerve terminals (synaptosomes, SYNs), neurotransmitters (NTs) are stored in synaptic vesicles (SVs) (10,11). Release of NTs at the presynaptic active zone occurs through exocytosis of SVs described by the SV cycle consisting of vesicle docking, priming and fusion. SVs of the readily releasable pool sense the increase in cytosolic Ca^{2+} induced by the action potential that opens voltage-gated Ca^{2+} channels (12). Ca^{2+}-bound synaptotagmin acting as Ca^{2+} sensor (13) recruits to assembled soluble NSF attachment protein receptor (SNARE) complexes, reverse the action of complexins clamping the assembled SNAREs (14,15) and initiate fusion, while Sec1/Munc18-like proteins engage the trans-SNARE complexes to direct their fusogenic activity. In the cycle, the NT release is followed by clathrin-dependent endocytosis or reuptake through specific intracellular transport systems (16,17).

Although there is consensus that biological membrane fusion depends on SNARE complexes and Sec1/Munc18-like proteins, conditions are known that induce fusion of pure lipidic membranes. Accumulating evidence suggests that the mechanisms directing fusion of biomembranes and membranes of pure lipids involve common sets of intermediate stages. When fusion is initiated membranes no longer are in a planar bilayer (lamellar) shape, but rather adopt highly curved non-bilayer (non-lamellar) formations (18). Non-lamellar lipids, such as phosphatidylethanolamine (PE) and plasmenylethanolamine have the propensity to assemble into curved monolayers forming inverted H_{II} hexagonal phases that facilitate fusion (18–21). Fusion proceeds by formation of an initial stalk-like intermediate (22) leading to a hemifusion stage distinguished by fusion of the contacting monolayers (19,22). NTs such as monoamines, glutamate (Glu) and acetylcholine (ACh) are taken up from the cytosplasm into SVs by vesicular NT transporters. Transport usually involves exchange of vesicular H^+ for cytoplasmic transmitter. Thus, transport depends on an H^+ electrochemical gradient generated by the vesicular H^+ ATPase (23). Acidification is strongly supported by vesicular chloride channels, indicating the important role of ΔpH in vesicular NT transport. However, NT transporters are differently affected by the H^+ gradient. While ACh transport primarily depends on ΔpH, vesicular Glu transport predominantly depends on the vesicular membrane potential and is less influenced by H^+ exchange (24).

The most representative ELs in the human and rodent brain are PLs of the type alkenylacyl PE (plasmenylethanolamine) accounting for ∼20% of total brain phospholipids, while alkylacyl phosphatidylcholine (PC) (plasmanylcholine) and alkylacyl PE (plasmanylethanolamine) make up ∼2% (25,26). Other physiologically relevant mammalian lipids containing ether-linked alkyl chains are platelet-activating factor (alkylacetyl PC), sulfogalactosyl alkylacylglycerol (seminolipid) abundant in the testis and the lipid moiety of most glycosyl phosphatidylinositol (GPI)-anchored proteins (27–30). GPI-anchored proteins specifically enrich in lipid raft microdomains (LRMs) that in neural and other tissues act as platforms for signal transduction (31). LRMs are highly dynamic ∼20 nm structures (32) that in addition to GPI-anchored and other LRM-associated proteins are also enriched in cholesterol, glycosphingolipids and, as recently noted, PLs (4,31,33).

Starting with the idea that developmental defects in the CNS of EL-deficient mice may originate from reduced synaptic activity (5) or impaired functioning of LRMs (34,35), we investigated the Glu and ACh release from control and EL-deficient isolated cortical SYNs. Here, we report that EL deficiency affects the energy state and lipid composition of cortical SYNs resulting in the significant reduction in the NT release. The results may be interpreted as effects of EL deficiency on the imbalance of intracellular ion homeostasis with serious consequences in mitochondrial energy coupling and ER stress response.

RESULTS

Numerous studies have demonstrated the usefulness of synaptosomal preparations to investigate the presynaptic NT release (36). As isolated nerve terminals no longer are subject to depolarization by the action potential, depolarizing conditions applied *in vitro* are, for example, high external K^+ concentrations (30–60 mM) replacing Na^+, inhibition of K^+ channels by 4-aminopyridine or activation of Na^+ channels by veratridine. In this study, we used elevated K^+ that generates a single-clamped depolarization of the plasma membrane opening voltage-dependent Ca^{2+} channels. As a consequence, cytosolic Ca^{2+} levels increase triggering a biphasic, Ca^{2+}-dependent release of NTs (37). Both release of endogenous transmitters (Glu, ACh) and transmitters released following uptake of [^{3}H]-Glu or [^{3}H]-Ch into isolated SYNs were investigated.

Release of Glu

Glu is released from SYNs by two distinct mechanisms, Ca^{2+}-dependent exocytosis and Ca^{2+}-independent efflux from the cytoplasm. To distinguish between both mechanisms, two separate determinations were carried out, one in the presence of Ca^{2+} measuring both Ca^{2+}-dependent and -independent release, and one in the presence of ethylene glycol tetraacetic acid (EGTA) measuring the Ca^{2+}-independent efflux only.

About 80% of synapses in rodent CNS are glutamatergic. Thus, Glu concentrations in CNS are high and can accurately be determined by a fluorimetric assay linked to the enzymatic production of NADPH. No significant differences in the total brain Glu content were observed (Fig. 1A). Whereas the release of Glu from control and EL-deficient SYNs was about the same in the absence of Ca^{2+} (Fig. 1D), in its presence Glu release from EL-deficient SYNs was significantly reduced by 14% (Fig. 1C), indicating that the 58% reduction seen in EL-deficient SYNs (Fig. 1B) was largely due to reduced Ca^{2+}-dependent exocytosis rather than Ca^{2+}-independent efflux.

A similar difference in Ca^{2+}-dependent release between wild-type and EL-deficient SYNs was noted when the Glu

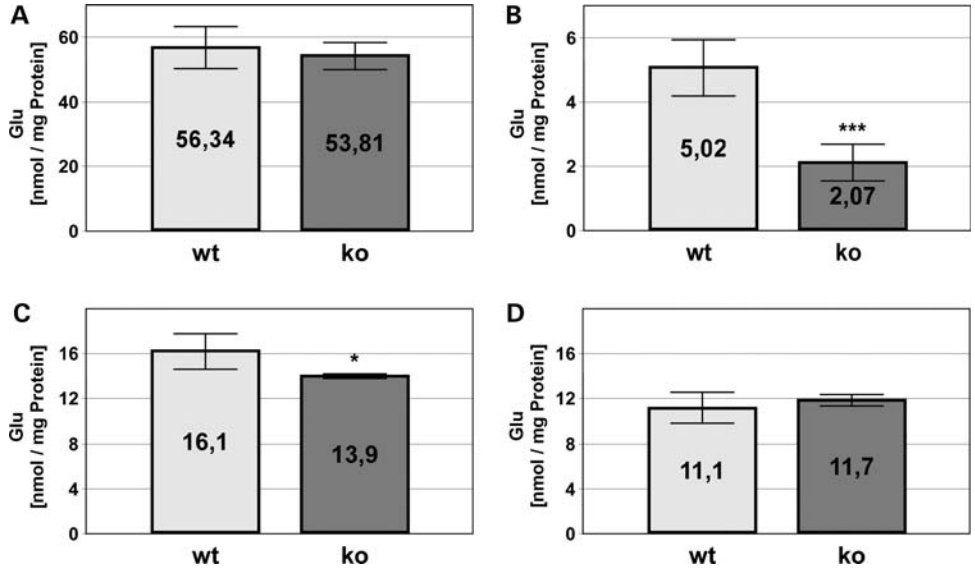

Figure 1. Glu release from isolated cortical SYNs of wild-type (WT) and EL-deficient (KO) mouse brain. Total Glu content (0.5% Triton X-100) (**A**) and release in presence of 1.3 mM Ca^{2+} (**B** and **C**) and 1 mm ethylene glycol tetraacetic acid (EGTA) (**D**) from SYNs (400 μg) were determined. The Ca^{2+}-dependent release is shown in (B). Values represent means ± SD of three to five independent experiments. $^{*}P \leq 0.05$, $^{***}P \leq 0.001$.

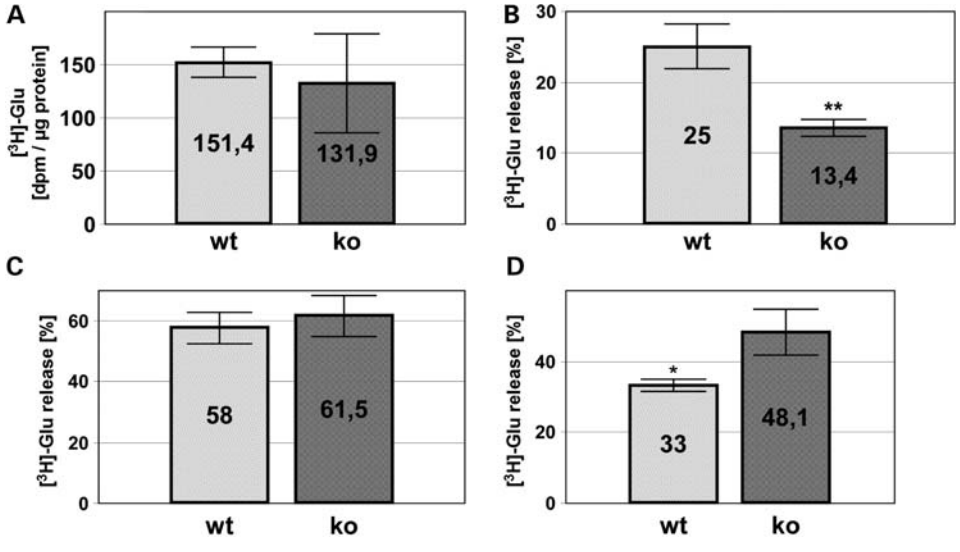

Figure 2. [^{3}H]-Glutamate ([^{3}H]-Glu) uptake and release from isolated cortical SYNs of the wild-type (WT) and EL-deficient (KO) mouse brain. SYNs (300 μg) were incubated with 0.5 μCi [^{3}H]-Glu for 15 min prior to analyzing uptake (**A**) and release in the presence of 1.3 mM Ca^{2+} (**B** and **C**) and 1 mM EGTA (**D**). The Ca^{2+}-dependent release is shown in (B). Values represent means ± SD of three independent experiments. $^{*}P \leq 0.05$, $^{**}P \leq 0.01$.

release was analyzed following [^{3}H]-Glu uptake into isolated nerve terminals (Fig. 2B). Total uptake into wild-type and EL-deficient SYNs was not significantly different (Fig. 2A). However, EL-deficient SYNs compared with controls released significantly higher quantities of Glu in the absence (Fig. 2D) but not in the presence of Ca^{2+} (Fig. 2C), resulting in a 45% decrease in Ca^{2+}-dependent exocytosis (Fig. 2B).

To investigate in more detail the availability of Ca^{2+} to the exocytotic machinery, release experiments were conducted using the $Ca^{2+}/2H^{+}$ ionophore ionomycin. When ionomycin at a concentration of 5 μM was added to the SYN suspension 1 min prior to Ca^{2+} (Fig. 3B) or EGTA (Fig. 3C) and 4 min prior to K^{+} elevation, Ca^{2+}-dependent Glu exocytosis in EL-deficient SYNs was reduced by 45% when compared with the wild-type (Fig. 3A). Furthermore, the quantity of Glu released from both wild-type and EL-deficient SYNs increased by a factor of three compared with the release without ionophore, suggesting additional Ca^{2+} availability generated by the ionophore (Figs 1B and 3A). Interestingly, while ionomycin in the absence of Ca^{2+} was without effect on wild-type SYNs (Fig. 1D and 3C), in EL-deficient ones it caused a >50% increase in Glu release (Fig. 3C). Thus, the difference between wild-type and EL-deficient SYNs in Ca^{2+}-dependent exocytosis mainly has to be ascribed to this increase in Ca^{2+}-independent efflux.

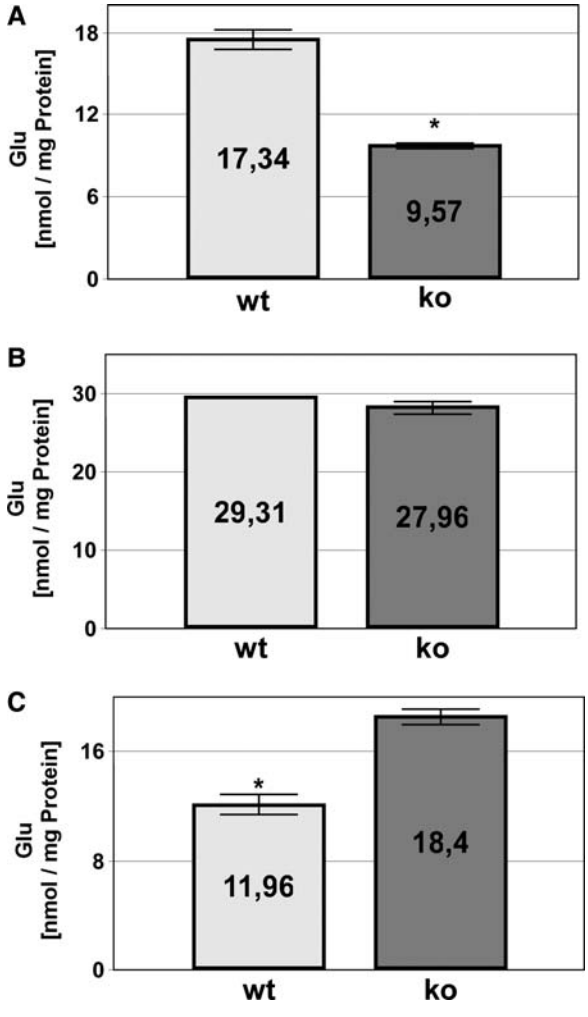

Figure 3. Release of Glu from isolated cortical SYNs of wild-type (WT) and EL-deficient (KO) mouse brain in the presence of ionomycin. SYNs (400 μg) were incubated with 5 μM ionomycin prior to the addition of 1.3 mM Ca^{2+} (**B**) and 1 mM EGTA (**C**). The Ca^{2+}-dependent release obtained by the difference in release in the presence (B) and absence (C) of Ca^{2+} is shown in (**A**). Values represent means ± SD of three independent experiments. $^{*}P \leq 0.05$.

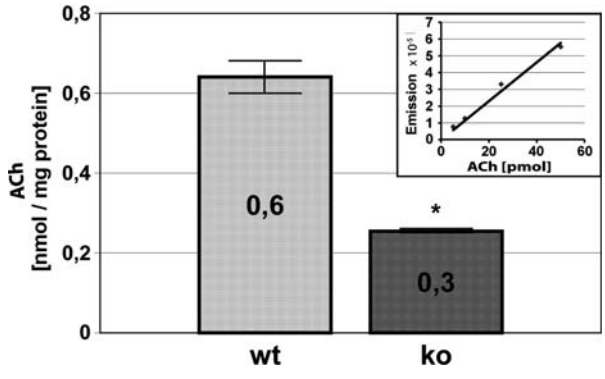

Figure 4. ACh release from isolated cortical SYNs of wild-type (WT) and EL-deficient (KO) mouse brain. The Ca^{2+}-dependent release, i.e. the difference between the release from SYNs (400 μg) in the presence of 1.3 mM Ca^{2+} and 1 mM EGTA is shown. The inset demonstrates the linearity of the assay. Values represent means ± SD of three to five independent experiments. $^{**}P \leq 0.01$.

Release of ACh

Release of both endogenous ACh and [^{3}H]-ACh synthesized following [^{3}H]-Ch uptake was determined in wild-type and EL-deficient SYNs by a similar protocol as used for the Glu studies. Endogenous ACh was determined by the luminometric choline oxidase assay (inset to Fig. 4) following the ACh esterase cleavage (38). Ca^{2+}-dependent ACh release induced by high external K^+ and determined as the difference in the presence and absence of Ca^{2+} was significantly reduced by 50% in EL-deficient SYNs (Fig. 4). No significant difference was seen between wild-type and EL-deficient SYNs in both uptake of [^{3}H]-Ch and release of [^{3}H]-ACh from prelabeled SYNs in the presence of Ca^{2+} (Fig. 5A and C). However, Ca^{2+}-independent efflux of [^{3}H]-ACh was remarkably increased in EL-deficient SYNs (Fig. 5D) resulting in a significant 32% reduction in Ca^{2+}-dependent [^{3}H]-ACh exocytosis (Fig. 5B).

In summary, exocytosis of both endogenous ACh and Glu was reduced in EL-deficient SYNs by ∼60%, respectively (Fig. 6A). Following uptake of [^{3}H]-labeled Glu or Ch, the Ca^{2+}-dependent release of [^{3}H]-Glu and [^{3}H]-ACh was impaired in EL-deficient SYNs by 47 and 31%, respectively (Fig. 6B).

Synaptosomal energy requirement

As exocytosis of NTs from SYNs is an energy-consuming process (39), we analyzed the respiratory capacity of free cortical mitochondria and SYNs using a Clark-type electrode. The rate of respiration of free wild-type and EL-deficient mitochondria neither in the absence nor presence of additional substrates, such as succinate or succinate plus adenosine diphosphate (ADP) was significantly different (Fig. 7A). However, synaptosomal respiration differed from that of free mitochondria in two respects. First, in the medium containing 10 mM glucose EL-deficient SYNs respired at a rate 28% decreased compared with wild-type SYNs (Fig. 7B). Secondly, upon depolarization in the presence of Ca^{2+} the rate of respiration of wild-type SYNs increased significantly, whereas EL-deficient SYNs completely failed to adapt respiration to the consequences of depolarization (Fig. 7B). According to the reduced respiratory capacity of EL-deficient SYNs, the adenosin-5′-triphosphate (ATP) content was also significantly diminished by 27%, while ADP concentrations in wild-type and EL-deficient SYNs were largely the same. As a consequence, the ATP/ADP ratio in EL-deficient SYNs was decreased by 23% (Table 1). Thus, the lack of synaptosomal ELs caused an impaired energy balance that might well contribute to the disturbed NT exocytosis.

Analysis of synaptosomal lipids

Presynaptic signaling depends on membrane-localized processes, such as vesicle exocytosis and functioning of various ion channels and pumps. Therefore, we investigated by lipidomic analysis the impact of EL deficiency on synaptosomal membrane lipid composition (Table 2 and Supplementary

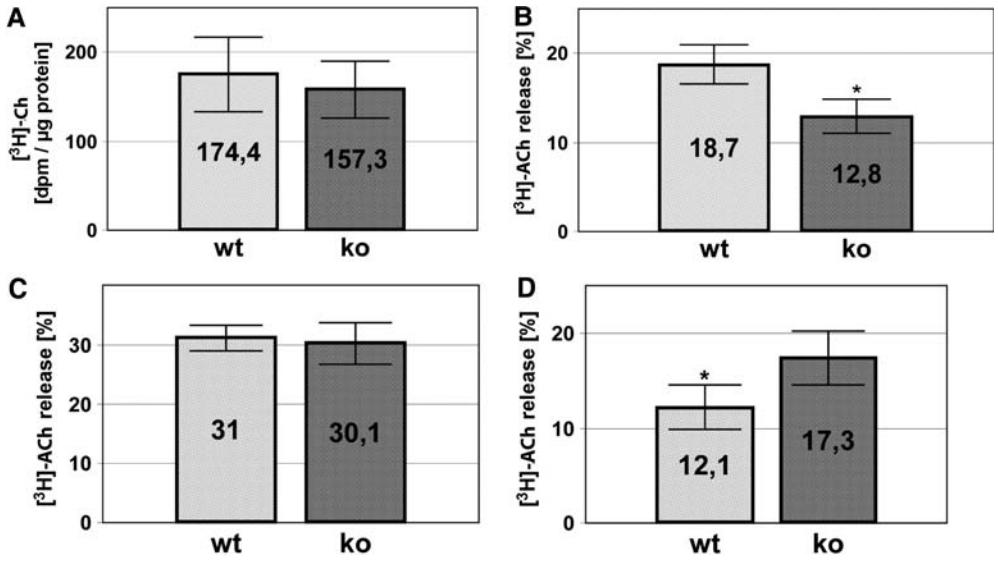

Figure 5. [^{3}H]-Choline ([^{3}H]-Ch) uptake and [^{3}H]-acetylcholine ([^{3}H]-ACh) release from isolated cortical SYNs of wild-type (WT) and EL-deficient (KO) mouse brain. SYNs (300 µg) were incubated with 2 µCi of [^{3}H]-Ch for 30 min prior to analyzing uptake (**A**) and release in the presence of 1.3 mM Ca^{2+} (**B** and **C**) and 1 mM EGTA (**D**). The Ca^{2+}-dependent release is shown in (B). Values represent means ± SD of three independent experiments. $^*P \leq 0.05$.

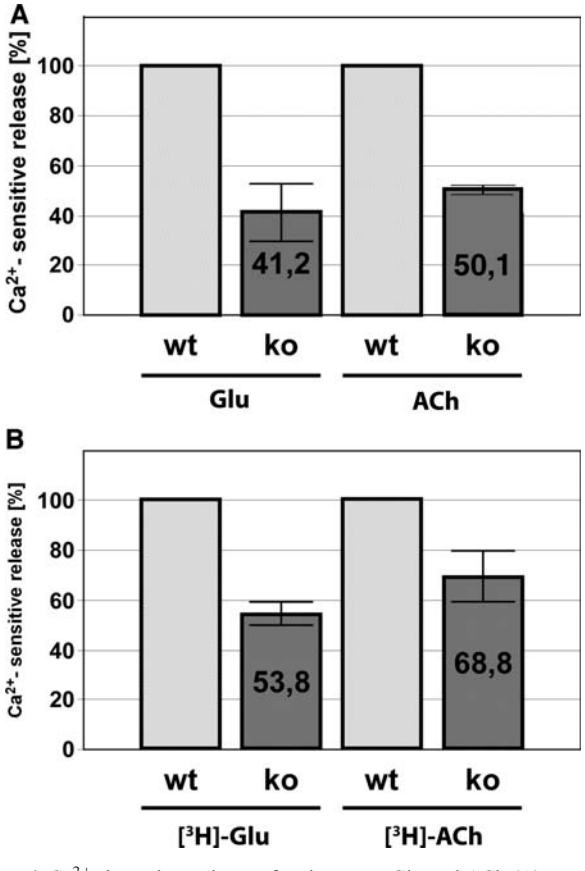

Figure 6. Ca^{2+}-dependent release of endogenous Glu and ACh (**A**) as well as [^{3}H]-glutamate ([^{3}H]-Glu) and [^{3}H]-acetylcholine ([^{3}H]-ACh) (**B**) after [^{3}H]-Glu and [^{3}H]-choline ([^{3}H]-Ch) uptake into isolated cortical SYNs of wild-type (WT) and EL-deficient (KO) mouse brain. Values represent means ± SD of three to five independent experiments. $^{**}P \leq 0.01$.

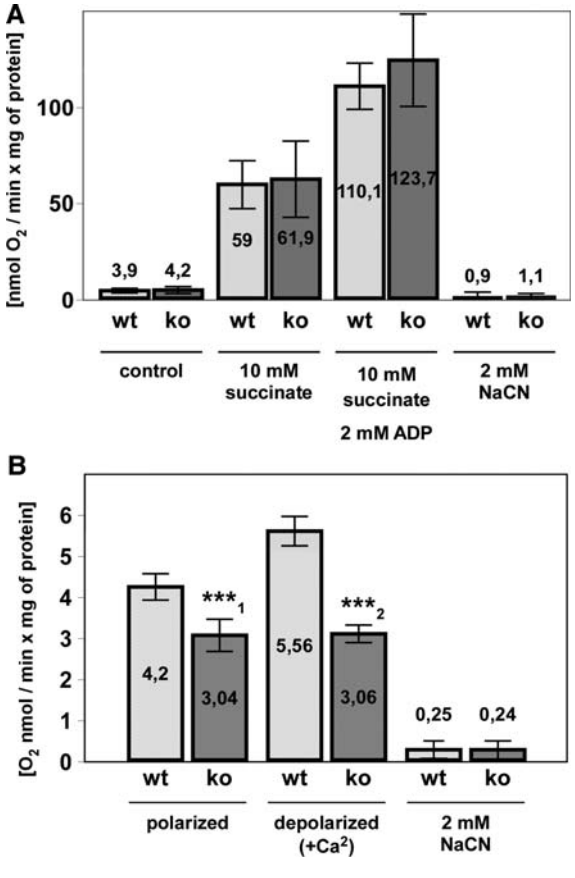

Figure 7. Rate of respiration of free cortical mitochondria and SYNs of wild-type (WT) and EL-deficient (KO) mouse brain. Oxygen consumption of free mitochondria (125 µg) was determined in the presence of succinate, succinate plus adenosine diphosphate (ADP) and cyanide (**A**). Respiration of SYNs (750 µg) in the presence of 10 mM glucose and 1.3 mM Ca^{2+} (**B**). Note that under depolarizing conditions, WT SYNs increase respiratory rate by 25% compared with the polarized state, while KO SYNs are unable to do so. Values are means ± SD of three to five independent experiments. $^{***}P \leq 0.001$.

Material, Table S1). In wild-type SYNs, PLs contributed to total lipids by 14%. Their lack in mutants caused an increase mainly in the concentration of PE by ~50% raising the percentage of PE from 17% in wild-type to 28% in EL-deficient SYNs. In spite of the general increase in PEs, the major PE species in wild-type SYNs PE 40:6 decreased, whereas PE 38:4 increased more than 2-fold in concentration in EL-deficient SYNs. Although there were remarkable changes in the relative concentrations of PEs, the concentration of polyunsaturated fatty acids (PUFAs) in total synaptosomal membranes of EL-deficient SYNs were fairly the same (292.91 nmol/mg of the protein) as that in the wild-type (321.36 nmol/mg of the protein). A similar tendency as seen in isolated SYNs was to be observed in LRM preparations where PLs contributed 23% to total lipids. EL deficiency led to an increase in PE from 8% in the wild-type to 22% in EL-deficient LRMs. All PE species were increased in EL-deficient LRMs by factors between 1.6 (PE 38:6) and 4.1 (PE 36:2) except PE 40:6 that remained in concentration as in wild-type LRMs. Again PE 38:4 was the dominant species in EL-deficient LRMs.

EL deficiency also caused subtle changes in the relative proportion of various PC, SM and PS species (Supplementary Material, Table S1). PC concentrations decreased by ~10% both in intact SYNs and their LRMs. Interestingly, PC 38:6 and PC 40:6 were lowered in EL-deficient SYNs and their LRMs to about half the amount present in wild-type, suggesting fine-tuning of the synaptosomal membrane fluidity. SM slightly increased and became enriched in LRMs by a factor of about 3. For PS, we recognized in LRM preparations of both wild-type and EL-deficient SYNs a remarkable increase in the concentration of the less-unsaturated species PS 36:1 at the expense of PS 40:6, suggesting PS to be involved in regulating of LRM fluidity.

Table 1. ATP and ADP content of re-energized cortical SYNs of wild-type (WT) and EL-deficient (KO) mouse brain

Condition	Tissue	ATP (nmol/mg of protein)	ADP (nmol/mg of protein)	ATP/ADP ratio
Re-energized	WT	3.11 ± 0.41	1.34 ± 0.3	2.37 ± 0.24
	KO	2.26 ± 0.35	1.24 ± 0.21	1.82 ± 0.12
% Change		−27*	−7	−23*

Values represent means ± SD of three independent experiments.
*$P \leq 0.05$.

Table 2. PE, plasmenylethanolamine (PL-PE) and cholesterol content of SYNs and synaptosomal LRMs of WT and EL-deficient (KO) mouse brain

m/z	Species	Synaptosomes (nmol/mg of protein)		LRMs (nmol/mg of protein)	
		WT	KO	WT	KO
PE					
718	34:1	2.33 ± 0.33	4.29 ± 0.33	5.66 ± 0.92	14.19 ± 1.35
740	36:4	3.44 ± 0.19	7.33 ± 0.66	2.90 ± 0.04	10.46 ± 1.63
744	36:2	3.00 ± 0.25	7.80 ± 0.71	5.54 ± 0.15	22.78 ± 3.51
746	36:1	3.91 ± 0.16	7.65. ± 0.34	17.21 ± 1.90	33.01 ± 5.58
764	38:6	10.74 ± 0.81	14.11 ± 1.92	7.68 ± 0.01	12.41 ± 2.18
768	38:4	34.56 ± 0.98	79.11 ± 6.42	26.35 ± 0.68	94.53 ± 14.6
792	40:6	55.09 ± 4.44	46.50 ± 5.32	35.91 ± 4.55	34.95 ± 6.77
796	40:4	5.41 ± 0.22	10.12 ± 1.27	7.99 ± 0.70	22.09 ± 3.20
Total		118.48	176.91	109.24	244.42
PL-PE					
702	16:1–18:1 18:2–16:0	6.29 ± 0.25	n.d.	31.51 ± 4.43	n.d.
724	16:1–20:4	3.48 ± 0.35	n.d.	3.06 ± 0.24	n.d.
728	18:2–18:1 16:1–20:2	7.31 ± 0.33	n.d.	47.64 ± 8.27	n.d.
730	18:1–18:1 16:1–20:1	7.19 ± 0.10	n.d.	66.84 ± 9.04	n.d.
748	16:1–22:6	9.96 ± 0.60	n.d.	6.64 ± 0.25	n.d.
750	18:2–20:4 16:1–22:5	6.30 ± 0.80	n.d.	11.19 ± 1.52	n.d.
752	16:1–22:4 18:1–20:4	13.08 ± 0.43	n.d.	29.43 ± 3.87	n.d.
756	18:2–20:1 18:1–20:2	2.55 ± 0.21	n.d.	26.18 ± 3.60	n.d.
758	18:1–20:1 18:2–20:0	1.78 ± 0.02	n.d.	26.09 ± 2.31	n.d.
774	18:2–22:6	4.51 ± 0.11	n.d.	2.82 ± 0.62	n.d.
776	18:1–22:6	21.07 ± 0.14	n.d.	23.69 ± 2.50	n.d.
778	18:2–22:4 18:1–22:5	5.52 ± 0.46	n.d.	11.29 ± 2.03	n.d.
780	18:1–22:4	5.95 ± 0.14	n.d.	20.93 ± 4.72	n.d.
Total		94.99		307.31	
Cholesterol		192.6 ± 28.7	160.0 ± 10.2	366.7 ± 35.1	353.3 ± 41.6

Values represent means ± SD of two to five independent experiments; n.d., not detected.

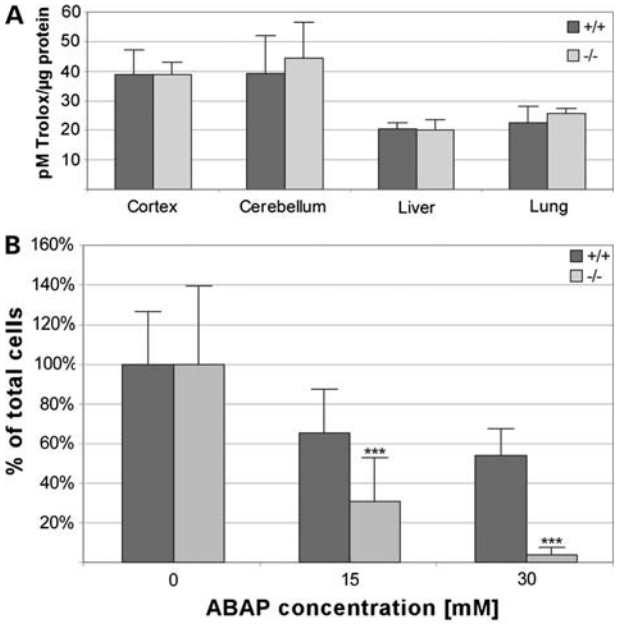

Figure 8. TRAP of various tissues (**A**) of wild-type (WT) and EL-deficient (KO) mice and resistance of WT and KO mouse fibroblasts against 2,2′-azobis(2-methylpropionamidine) 2 HCl (ABAP)-induced oxidative stress (**B**). Values in (A) are means ± SD of three independent experiments. $^{***}P \leq 0.001$.

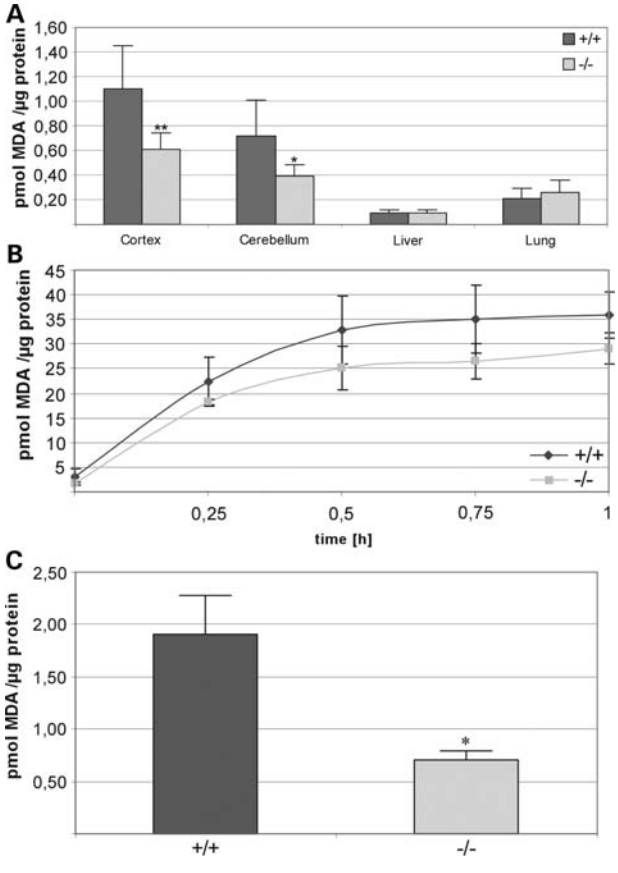

Figure 9. TBARS of wild-type (+/+) and EL-deficient (−/−) tissues (**A**) as well as Fe^{2+}/ascorbate-induced TBARS in +/+ and −/− mouse brain cortical homogenate (**B**) and lipid extracts (**C**). The assay predominantly measures the concentration of MDA. Values represent means ± SD of three independent experiments. $^{*}P \leq 0.05$, $^{**}P \leq 0.025$.

Oxidative stress in EL-deficient tissues

PLs are known to be more susceptible to oxidative attack than normal phospholipids. This observation led to the proposal of PLs to protect cells from oxidative stress (1,26,40–42). As most of the studies dealing with this subject were carried out *in vitro*, we investigated the anti-oxidative status of selected PL-deficient tissues in order to correlate potential oxidative tissue damage with the observed impairment of presynaptic transmitter release. To this end, Total reactive antioxidant potential (TRAP), total GSH and GSSG as well as thiobarbiturate-reactive substances (TBARS) were determined.

TRAP measurements provide important information on the capacity of tissues to withstand oxidative stress imbalance. The method usually implies thermolytically generated 2,2′-azobis(2-methylpropionamidine) 2HCl (ABAB) radicals that in the presence of luminol induce luminescence (43). TRAP is usually quantified by estimating the concentration of Trolox, a synthetic antioxidant, producing the same quenching of luminescence as the tissue under investigation. As shown in Figure 8A, the equivalent Trolox concentrations in tissues with and without PLs were the same. Thus, PLs do not significantly add to TRAP of the brain, lung and liver, tissues that have high, intermediate and very low PL concentrations, respectively (25).

Furthermore, we investigated ABAP-induced oxidative attack on the viability of wild-type and EL-deficient mouse fibroblasts. The results demonstrate the concentration-dependent decrease in viability that was significantly more pronounced in cells lacking PLs (Fig. 8B).

Many tissues including the brain contain GSH concentrations that are in the millimolar range (44). The GSH–GSSG system is one of the most important cellular means defending oxidative stress. PL deficiency did not cause a significant change in the level of GSH and GSSG except the slight increase in GSSG in liver where PL concentrations are very low (Supplementary Material, Fig. S1) (25).

TBARS are a widely used marker indicating the extent of cellular lipid peroxidation. The assay largely determines the concentration of malondialdehyde (MDA), a major oxidation product derived from PUFAs (45). Surprisingly, in the CNS of both the cortex and cerebellum, PL deficiency caused a significant reduction in TBARS by ∼40%. No such changes were found in the liver and lung (Fig. 9A). As these results were in contradiction to previous reports (41), we further studied iron/ascorbate-induced MDA production in cortical brain homogenates and lipid extracts. In brain homogenates lacking PLs, MDA production was delayed during the 1 h oxidation period compared with controls, although the observed differences were statistically not significant (Fig. 9B). In line with these experiments, we noted in lipid extracts from PL-deficient cortical tissue significantly less MDA when compared with normal tissue extracts (Fig. 9C). These data suggest that PLs, although not detectably contributing to TRAP, at least in the brain considerably account for the formation of lipid peroxidation products.

mRNA microarray analysis

The remarkable alterations of SYN functions elicited by the deficiency of ELs raised the question as to changes in the expression level of functionally related genes. We therefore initiated microarray analysis comparing mRNA expression profiles of the control and PL-deficient cerebellum. Surprisingly, none of the genes closely related to the phenotypes seen in the PL-deficient brain (5) appeared to be altered. Instead, we found the down-regulated expression of a limited number of mRNAs, such as heat-shock protein 90b1 (Hsp90b1/Grp94/gp96), Hspa5 (BiP/Grp78), protein disulfide isomerase-associated 4 and 6 (PDI4, PDI6), X-box-binding protein 1 (XBP1) as well as arginine-rich mutated in early stage tumors (ARMET) and cysteine-rich with EGF-like domain 2 (CRELD2) (46,47), known to be related to the unfolded protein response (UPR) (48,49) (Supplementary Material, Table S2). These data indicate that PL deficiency by mechanisms that still have to be defined might be implicated in the regulation of the UPR possibly by affecting the IRE1α/XBP1 pathway.

DISCUSSION

Previous studies on the EL-deficient mouse model, particularly those on Purkinje cell innervation, suggested PLs to be required for correct functioning of presynaptic activity. The present analyses of NT release indeed demonstrated that the lack of PLs compromised presynaptic activity by both decreasing Ca^{2+}-dependent and increasing Ca^{2+}-independent release. How are these findings interpreted in terms of PL function? NT release is a strictly ATP-dependent process requiring functional synaptic mitochondria (36). As shown here, EL deficiency caused the reduction in synaptic respiratory activity and consequently the decrease in the ATP/ADP ratio by >20% (Fig. 7, Table 1). This decrease seems to be sufficiently high to account for the observed effects on Glu and ACh exocytosis as documented in a previous study on guinea pig SYNs (50). Inhibition of aerobic respiration by rotenone resulting in the time-dependent decrease in ATP by 25% reduced the Ca^{2+}-dependent Glu exocytosis by ∼30% and substantially enhanced the Ca^{2+}-independent Glu release. Quite similar observations were made in EL-deficient SYNs in which respiration and ATP levels were lowered by ∼30% resulting in a >40% decrease in Ca^{2+}-dependent exocytosis (Table 1, Fig. 6). The Ca^{2+}-independent increase was particularly striking either for the efflux of Glu by the Ca^{2+} ionophore ionomycin present during depolarization or SYNs were first loaded with [^{3}H]-Glu or [^{3}H]-Ch both raising the free cytoplasmic concentrations of the transmitters (51). A reasonable explanation might be that the lowered energy level impairs the activity of the Na^+/K^+ ATPase that in turn reduces the Na^+ gradient across the plasma membrane. Consequently, the Na^+-dependent Glu transporter, normally implicated in the removal from the synapse of released Glu, reverses, liberating cytoplasmic Glu in a Ca^{2+}-independent manner (52). The electrogenic nature of the Glu transporter in addition might attenuate the driving force for uptake during membrane depolarization further supporting transport reversal (53). The enhanced Ca^{2+}-independent release of Glu from the presynaptic terminal (Figs 2 and 3) and the inability of EL-deficient synaptic mitochondria to respond to the altered ion concentration gradients during depolarization strongly indicate dys-functioning of these mitochondria. As a consequence, their reduced level of ATP will delay recovery of the Na^+/K^+ gradient and result in sustained higher levels of cytoplasmic Ca^{2+}. In a negative feedback, enhanced cytoplasmic Ca^{2+} in turn might have serious consequences to mitochondrial activities, such as regulation of ion homeostasis and energy coupling (54). Moreover, recent lipidomic analysis indicated that brain and heart mitochondria contain significant quantities of PLs (55,56) and thus deficiency of PLs in mitochondria might definitely contribute to the synaptic impairment of EL-deficient SYNs. In addition to the mitochondrial compartment, the ER that is heavily implicated in phospholipid biosynthesis and Ca^{2+} homeostasis might also be affected by the lack of PLs. Surprisingly, cerebellar microarray analyses revealed the down-regulation of components of the UPR in the ER (49), suggesting PL deficiency to bias ER functions. Gene transcripts coding for XBP1, BiP/GRP78, Hsp90b1, PDI4, PDI6, CRELD2 and ARMET/MANF were significantly down-regulated without impairing other components of the UPR, such as IRE1α, PERK, ATF4 and ATF6. As the level of BiP determines the activities of PERK, IRE1α and ATF6 (57), ER stress response pathways might be generally affected. Hence, in case of acute stress, cells might be ill-prepared to respond and more susceptible to ER stress-induced death. The reduced level of XBP1 might play a central role in down-regulation of components of the UPR. XBP1 is activated by IRE1α to function as a pivotal transcription factor regulating both its own expression and that of BiP (58). In addition, XBP1 has also been shown to trigger lipid biosynthesis and biogenesis of the secretory apparatus (59). Thus, the reduced activity of XBP1 might well account for morphological and possibly functional impairments previously described in ER and Golgi of EL-deficient human skin fibroblasts (2).

The mass spectral lipid analyses of SYNs demonstrated subtle changes in membrane phospholipid composition due to EL deficiency. Particularly, the concentrations of individual species of PE were affected. Most of them increased, notably PE 38:4, while PE 40:6 decreased. These changes in the phospholipid composition obviously compensated for the lack of PLs especially PL 38:5, PL 38:7 and PL 40:7 (Table 2). The subtle changes in phospholipid composition might influence membrane fluidity (1), direct PL–protein interactions (20,60) or the function of 1-O-alkyl moiety-containing GPI-anchored proteins (29). However, to what extent these changes contribute to the overall effects of EL deficiency remains subject to further investigations.

A major role of PLs frequently discussed in the literature is their ability to protect cells against reactive oxygen species (ROS) and to function as endogenous antioxidants (26,61). While *in vitro* experiments accumulated substantial evidence for this function, the role of PLs *in vivo* in antioxidative defense still has to be defined. Oxidants found to elicit PL degradation include peroxyl radicals (62), UV light (26) and various transition metals (40,41,62,63). The labile vinyl ether bond at the sn-1 position of PLs appears to be target of direct oxidant reaction. Concomitantly, the oxidation of

PUFAs present in the reaction mixture directly bound to the sn-2 position of either PLs or other phospholipids (Table 2, Supplementary Material, Table S1) seems to be considerably delayed (40), suggesting PLs to have antioxidative properties. In line with this, the present results on PL-deficient tissue demonstrate significantly less MDA production compared with wild-type tissue supporting the view that PLs are a major source of MDA. Although PL-deficient tissues contain less MDA and possibly other toxic lipid peroxidation products (Fig. 9), such as various aldehydes and hydroxyaldehydes (63), lack of PLs significantly renders cells more susceptible to induced oxidative stress (Fig. 8B) (26,61). These mutually contradictory results might suggest that the continuous generation of ROS keeps cellular oxidative and antioxidative activities in balance. Reduced ROS production down-regulates the protective capacity rendering cells prone to sudden oxidative attack (Fig. 8B).

MATERIALS AND METHODS

Biological preparations

DHAPAT-null mice were generated as previously described (3,4). The animals were maintained in the breeding facility of the IBF of the University of Heidelberg and kept on a normal diet that did not contain detectable amounts of ELs. Mouse brain SYNs were prepared with slight modifications as described (64). The brain was removed and a 10% cerebral homogenate prepared using a 5 ml Potter homogenizer (0.1 mm clearance) and 10 up and down strokes at 700 rpm in 0.32 M sucrose adjusted to pH 7.4 (1 M HCl) containing ethylenediaminetetrqacetic acid (EDTA)-free protease inhibitors (Roche, Mannheim). Nuclei were removed at 1000*g* for 10 min and the supernatant centrifuged for 25 min at 15 000*g*. The pellet was re-suspended in 2 ml of 0.32 mM sucrose containing 0.25 mM dithiothreitol (DTT) and EDTA-free protease inhibitors adjusted to pH 7.4 and applied to a four-step Percoll gradient consisting of 0.5 ml of 50% (w/v) sucrose and 2.5 ml of 23%, 4.5 ml of 10% and 1.5 ml of 3% (w/v) Percoll dispersed in the same medium and centrifuged for 13 min at 32 500*g*. SYNs were located at the 10%/23% interphase and free mitochondria between 23% Percoll/50% sucrose.

LRMs were prepared as described in reference (65,66). SYNs (2 mg) were washed in the LRM buffer (10 mM Tris, 140 mM NaCl, 1 mM EDTA, 1 mM DTT, pH 7.4), transferred to a SW41 tube and gently mixed with the same amount of LRM buffer containing 2% TX-100. The sample was incubated on ice for 30 min and vortexed every 5 min for 5 s. Using 60% (v/v) Optiprep, the suspension war adjusted to 40% final concentration and overlayed with 5 ml 35% (v/v) Optiprep and 2 ml LRM buffer. Centrifugation was for 3 h at 150 000*g*. LRMs were recovered at the buffer/35% Optiprep interphase.

Transmitter release

Organelles were first reenergized for 20 min at 37°C/900 rpm (67) and subsequently incubated for 3 min at 37°C in the presence of either 1.3 mM Ca^{2+} or 1 mM EGTA before depolarization in the presence of 60 mM KCl for 3 min at 37°C. Samples were centrifuged at 20 000*g* for 5 min and the supernatant stored on ice until assayed. Ionomycin was used at a concentration of 5 μM added 1 min prior to the addition of Ca^{2+}. Glu was measured fluorometrically at wavelengths of 340 and 460 nm by monitoring the production of NADPH in an enzyme-coupled assay (Glu dehydrogenase type III, Sigma) using 400 μg of SYNs (68). At the end of each assay, 4 nmol Glu were added as an internal standard for quantification. Total Glu content of SYNs was measured by adding Triton X-100 [Roche, Mannheim, final conc. 0.5% (v/v)] to the reenergized samples and incubation for 2 min at 37°C/900 rpm.

To 400 μg reenergized SYNs, 5 μM hemicholinium-3 (Sigma, Munich) was added and ACh release initiated in the presence and absence of Ca^{2+} as described for Glu. ACh was measured enzymatically (choline oxidase *Alcaligenes sp.* and ACh esterase, *E. electricus*, horseradish peroxidase type III, Sigma, Munich) using the luminometric assay as described (38,69). Luminescence was read for 10 s (Berthold Lumat LB 9501). All samples were measured in triplicate.

Release of [^{3}H]-labeled NT

To 300 μg SYNs, 0.5 μCi [^{3}H]-Glu or 2 μCi [^{3}H]-choline ([^{3}H]-Ch) were added and the assays incubated for 15 min ([^{3}H]-Glu) or 30 min ([^{3}H]-Ch) at 37°C/900 rpm. Samples were chilled on ice and centrifuged for 5 min at 11 000*g*. Pellets were washed twice to remove unincorporated radioactivity and the resuspended organelles reenergized for 7.5 min at 37°C/900 rpm. Release was performed as described above for Glu and ACh. Radioactivity was determined by liquid scintillation counting.

Analytical procedures

The protein was determined by a modified Lowry method adding 0.2% SDS to the TCA-precipitated protein (70).

Synaptosomal ATP/ADP content was determined by using the ATP bioluminescence assay kit CLS II (Roche, Mannheim). In brief, 200 μg of SYNs were gently resuspended for re-energetization in 1 ml of HBM and incubated at 37°C at 900 rpm for 2 min (67). Thereafter, the sample was added to 4 ml of lysis buffer (95°C) and incubated for an additional 2 min at 95°C. After chilling on ice, the content was centrifuged for 5 min at 20 000*g* and the supernatant stored on ice. ADP determination was carried out by adding to 1 ml of supernatant 10 U of pyruvate kinase, 2 mM phosphoenol pyruvate and 10 mM $MgSO_4$ and incubating the assay for 15 min at 37°C and 900 rpm. The reaction was terminated by heating to 95°C for 2 min and centrifugation for 5 min at 20 000*g*. To 25 μl of supernatant 175 μl of reaction buffer and 50 μl of luciferase reagent were added and the resulting luminescence read for 10 s (Berthold Lumat LB 9501). All samples were measured in triplicate.

Cholesterol was determined fluorometrically by using the Amplex Red Kit (Invitrogen, Darmstadt) according to the instructions of the manufacturer. In brief, samples containing 1–3 μg of the synaptosomal protein were added to the reaction solutions and incubated for 30 min at 37°C in 96-well plates. Fluorescence intensity was analyzed in a plate reader

(Molecular Devices, SpectraMax Gemini XS) at wavelengths of 560 and 590 nm. Measurements were performed in triplicate.

Mass spectrometry analyses were done with a triple quadrupole instrument (QUATTRO II, Micromass) equipped with a nano-ESI source. The source temperature was set to 30°C and according to the ion mode a capillary voltage of ~600–900 V was applied. Lipid extraction was performed as described (71) adding lipid standards dissolved in chloroform/methanol (1:2) before extraction. Dried lipids were re-dissolved in methanol containing 10 mM ammonium acetate. Quantification of PC and SM was carried out as described (72) and PE and PS were determined by neutral loss scanning using a collision energy of 20 eV and selecting for a neutral loss of 141 or 185 Da (positive ion mode), respectively. PL-PE (plasmenyl ethanolamine) was assayed by precursor ion scanning for fragment ions 364, 390 and 392 Da (positive ion mode, using a collision energy of 18–20 eV) (72,73). Lyso-PL-PE was purchased from Matreya (Pleasant Gap, PA, USA). Quantifications were based on the phosphate content (74).

Oxygen consumption of synaptosomal and free brain mitochondria was determined by using a Clark electrode (OROBOROS® Instruments, Cylobios, Oxygraph, Innsbruck, Austria). Measurements were performed in duplicate. Briefly, 750 μg of SYNs or 125 μg of mitochondria were pelleted at 11 000*g* for 5 min and 4°C. SYNs were washed once with the hydroxyethyl piperazylethanesulfonic acid (HEPES)-buffered salt medium (118.5 mM NaCl, 4.7 mM KCl, 0.1 mM Na_2HPO_4, 1.18 mM $MgCl_2$, 20 mM HEPES, 10 mM glucose, pH 7.55) and mitochondria with Tris/phosphate-buffered salt medium (75 mM mannitol, 25 mM sucrose, 100 mM KCl, 10 mM KH_2PO_4, 0.5 mM EDTA, 5 mM $MgCl_2$, 20 mM Tris, 1 mg/ml bovine serum albumin, pH 7.55). The measurement chamber was loaded with 1.5 ml of the respective buffer and heated to 37°C. Following equilibration, the reenergized samples were added and the chamber closed. At the end of each experiment, 100 μl of concentrated $N_2S_2O_4$ was added to remove oxygen. Calculations were performed with DatLab Analysis 2.1.

Analysis of oxidative stress

TRAP was measured as described (43). Briefly, cerebrum, cerebellum, liver and lung were removed and homogenized in 140 mM KCl/20 mM phosphate buffer pH 7.4 (KP buffer). The assay in a total volume of 3 ml phosphate-buffered saline pH 8.6 contained 20 mM 2,2′-azobis(2-methylpropionamidine) 2 HCl (ABAP) and 5 μM 3-aminophthalhydrazide (luminol) and was incubated at room temperature. The water-soluble vitamin E analog 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid (Trolox) was used as a standard.

TBARS were measured exactly as described (75) and reduced (GSH) and oxidized (GSSG) glutathione determined as in reference (76). MDA generated by iron/ascorbate-induced fatty acid oxidation was assayed as described (41) using homogenized tissue in a total volume of 100 μl KP buffer, 20 μM $FeCl_2$ and 250 μM ascorbate. The oxidation reaction was followed over 1 h at 37°C and stopped by the addition of 1 mM desferal and 200 μM butylated hydroxytoluene. TBARS were determined as described above.

For statistical evaluation, Student's *t*-test was applied. Experiments were repeated two to five times and results represented as means ± SD.

SUPPLEMENTARY MATERIAL

Supplementary Material is available at *HMG* online.

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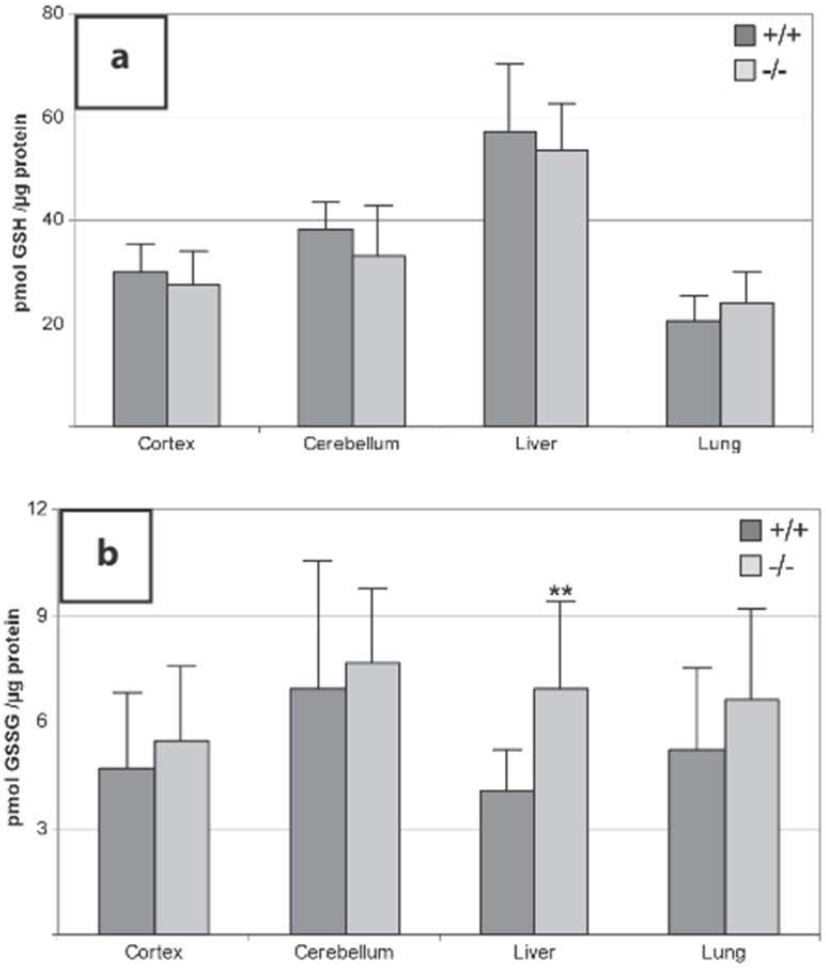
Supplementary Figure 1. Content of reduced (GSH) (a) and oxidized (GSSG) (b) glutathione in wild type (wt) and EL-deficient (ko) tissues. Values are means ± s.d. of 3 independent experiments. (**) $p \leq 0.025$.

Supplementary Table 1. Phosphatidylcholine (PC), sphingomyelin (SM) and phosphatidylserine (PS) content of SYNs and synaptosomal lipid raft microdomains (LRMs) of wild type (wt) and EL-deficient (ko) mouse brain.

Supplementary Table 2. Cerebellar (P15) mRNA microarray analyses in wild type and EL-deficient mouse brain of selected chaperons and components of the unfolded protein response.

Supplementary Figure 1



Supplementary Table 1

		Synaptosomes		LRMs	
		wt	ko	wt	ko
m/z	Species	[nmol / mg of Protein]		[nmol / mg of Protein]	
PC					
734	32:0	29.74±1.20	21.12±0.34	88.15±10.23	62.34±1.45
760	34:1	65.30±2.55	69.93±1.17	135.74±19.77	121.66±6.97
782	36:4	14.61±0.31	14.95±0.47	6.71±0.91	7.05±1.76
786	36:2	6.36±0.05	8.57±0.70	9.51±1.79	12.29±1.32
788	36:1	19.74±0.77	20.43±0.79	82.53±13.18	72.17±5.77
806	38:6	12.55±1.41	6.34±0.02	5.75±0.99	2.79±0.86
810	38:4	15.12±0.30	14.34±0.25	8.89±0.62	8.71±1.39
834	40:6	8.01±0.66	3.61±0.06	4.23±0.61	1.89±0.54
Total		171.43	159.29	341.51	288.90
SM					
701	N16:1	3.14±1.18	3.70±0.54	6.79±0.51	4.74±1.12
703	N16:0	3.00±0.33	3.17±0.25	3.46±0.21	5.03±0.21
729	N18:1	1.22±0.03	1.49±0.10	5.73±0.06	7.04±0.49
731	N18:0	7.66±1.11	9.26±0.68	20.06±2.25	36.64±2.80
757	N20:1	0.07±0.01	0.26±0.04	0.81±0.17	0.47±0.06
759	N20:0	0.98±0.13	1.26±0.44	3.68±0.54	3.81±1.10
785	N22:1	1.92±1.13	2.27±0.05	3.44±0.01	3.21±0.64
787	N22:0	1.25±0.76	1.02±0.50	6.19±0.28	3.99±0.01
811	N24:2	1.80±1.21	2.44±0.32	5.98±3.49	4.56±1.55
813	N24:1	3.46±1.68	4.48±0.86	18.00±0.70	31.89±1.63
815	N24:0	1.04±0.11	1.30±0.17	3.34±0.98	3.90±0.87
Total		25.54	30.65	77.48	105.28
PS					
790	36:1	10.31±1.42	10.22±2.94	61.45±3.12	45.68±7.81
812	38:4	4.85±0.35	10.60±0.92	18.24±1.38	21.16±0.33
818	38:1	0.97±0.29	1.20±0.74	8.92±1.18	5.05±0.81
836	40:6	78.10±0.80	73.98±8.38	44.48±0.04	30.48±4.24
840	40:4	9.01±1.12	11.92±2.50	16.60±1.58	17.88±0.65
Total		103.24	107.92	149.69	120.25

Supplementary Table 2
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Gene	Fold Change	Adjusted P-Value	P-Value	Description
Hspa5	0,598	0,013	3.207E-07	heat shock protein 5
Hsp90b1	0,642	0,031	1.182E-05	heat shock protein 90kDa beta (Grp94), member 1
Xbp1	0,584	0,031	4.163E-06	X-box binding protein 1
Creld2	0,542	0,030	1.964E-06	cysteine-rich with EGF-like domains 2
Armet	0,556	0,031	4.013E-06	arginine-rich, mutated in early stage tumors
C330006P03Rik	0,434	0,040	6.150E-06	RIKEN cDNA C330006P03 gene
Pdi6	0,618	0,041	7.329E-6	protein disulfide isomerase associated 6
Pdi4	0,663	0,045	1.179E-05	protein disulfide isomerase associated 4