



Identification of novel mammalian phospholipids containing threonine, aspartate, and glutamate as the base moiety[☆]

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ABSTRACT

In this study, we showed the occurrence of phosphatidyl-L-threonine (PThr), phosphatidyl-L-aspartate (PAsp), and phosphatidyl-L-glutamate (PGlu) in rat brain. Analyses using an HPLC–ESI–MS and an amino acid analyzer showed the presence of L-threonine, L-aspartate, and L-glutamate in the acid-hydrolysates of phospholipids from porcine cerebrum, rat cerebrum, and rat liver. Results of ESI–MS/MS analyses with neutral loss scanning and product ion scanning suggest the presence of PThr-(18:0, 18:1), PThr-(18:0, 22:6), PAsp-(18:0, 18:1), PAsp-(18:0, 22:6), PGlu-(18:0, 18:1), and PGlu-(18:0, 22:6) in rat brain. This is the first study to identify 2 novel phospholipids, PAsp and PGlu, with a carboxylate–phosphate anhydride bond, in living organisms.

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1. Introduction

Phospholipids are the major lipid components of biological membranes, in which *sn*-glycero-3-phosphate is esterified at its C1 and C2 positions by fatty acids and at its phosphoryl group by various bases such as choline, ethanolamine, and serine. Thus far, only 2 types of L-amino acid-containing phospholipids, i.e., phosphatidylserine (PS) and phosphatidylthreonine (PThr), have been identified in biological samples. PS is a derivative of phosphatidic acid, in which a phosphoric acid is bound by an ester linkage to the hydroxyl group of a serine moiety. It is a component of mammalian cell membranes and plays an important role in biological

processes such as apoptosis [1–4] and cell signaling [5–8]. Although it was long believed that phosphatidyl-L-serine (L-PS) was the only PS occurring in living organisms [9–11], we recently discovered a D-serine-containing phospholipid, phosphatidyl-D-serine (D-PS), in rat cerebrum [12] and other tissues [13]. Meanwhile, PThr has been found in eggs [14], tuna muscle [15], polyoma virus-transformed hamster embryo fibroblasts [16], and hippocampal neurons cultured in a medium without serine [17]. However, it is still unclear whether PThr or D-PS plays any role in living organisms.

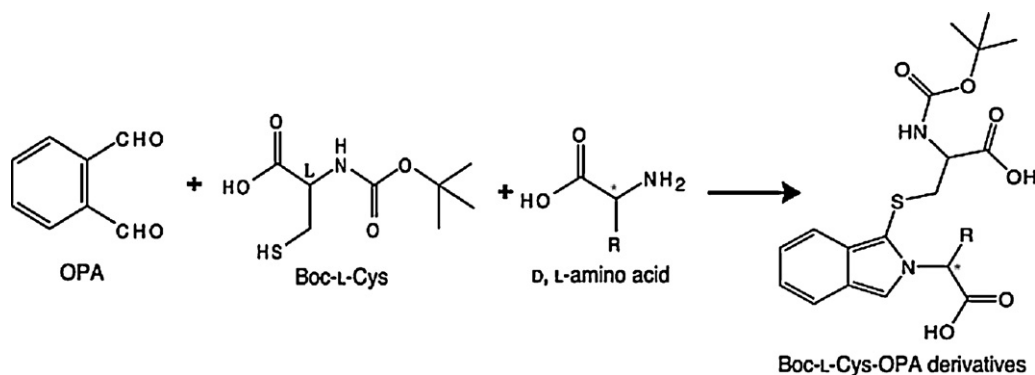
Both L-PS and PThr are synthesized by base-exchange reactions, in which the polar head groups of preexisting phospholipids are replaced by serine and threonine, respectively [17–20]. Similarly, D-PS has been suggested to be formed via a base-exchange mechanism, according to our previous finding of an endogenous activity through which free D-serine was incorporated into phospholipids from rat cerebrum extract [12]. This raises the question of whether other amino acids, besides serine and threonine, are incorporated as base moieties in phospholipids *in vivo*. In our previous studies [12,13], we have noticed that threonine, aspartate, and glutamate are also present in the lipid hydrolysates of rat tissues. In this study, we analyzed the hydrolysates of porcine cerebrum by using HPLC–ESI–MS analysis and those of rat cerebrum and liver by using an amino acid analyzer. Through ESI–MS/MS analysis of the phospholipids from rat cerebrum, we showed that threonine, aspartate, and glutamate indeed occurred as the head groups of phospholipids found in rat cerebrum. To our knowledge, this is

Abbreviations: Boc-L-Cys, *N*-tert-butylloxycarbonyl-L-cysteine; CEM, channel electron multiplier voltage; CM, carboxymethyl; DHA, docosahexaenoic acid; ESI, electrospray ionization; HPLC, high performance liquid chromatography; IS, ion spray voltage; MS, mass spectrometry; NMDA, *N*-methyl-D-aspartate; OPA, *o*-phthalaldehyde; OR, orifice voltage; PAsp, phosphatidyl-L-aspartate; PGlu, phosphatidyl-L-glutamate; PS, phosphatidylserine; L-PS, phosphatidyl-L-serine; D-PS, phosphatidyl-D-serine; PThr, phosphatidyl-L-threonine; RNG, focusing ring voltage; THF, tetrahydrofuran; TLC, thin-layer chromatography; 18:0, stearic acid; 18:1, oleic acid; 22:6, docosahexaenoic acid.

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Scheme 1. Derivatization of amino acid with OPA and Boc-L-Cys.

the first report of naturally occurring phospholipids possessing a carboxylate–phosphate anhydride bond.

2. Materials and methods

2.1. Materials

o-Phthalaldehyde (OPA) and a Cosmosil 5C₁₈-AR-II column (4.6 mm × 150 mm) were purchased from Nacalai Tesque (Kyoto, Japan). *N*-*tert*-Butyloxycarbonyl-L-cysteine (Boc-L-Cys) was purchased from Novabiochem (La Jolla, CA, USA). A preparative thin-layer chromatography (TLC) plate (Silica Gel 60 glass plate) was purchased from Merck (Darmstadt, Germany). A carboxymethyl (CM)-cellulose column was purchased from Whatman International Ltd. (Maidstone, UK). All other chemicals were of analytical grade.

2.2. Extraction and purification of lipids

Crude lipids were extracted from porcine brain (1 g) by using Folch's method [21]. To further purify the lipids, 0.2 volumes of 0.9% KCl was added to the crude lipid extract, and the mixture was centrifuged at 100 × *g* for 20 min at ambient temperature. The chloroform phase was collected and dried under a stream of nitrogen gas. The purified lipids were resuspended in chloroform and stored at –20 °C until use.

Male Std:Wistar rats (Japan SLC, Inc., Japan) at postnatal week 7 were euthanized and their cerebrums were extirpated. The extraction and purification of crude lipids were performed using the abovementioned procedures. PS-rich phospholipids were isolated from the purified lipids by preparative TLC by using the solvent system consisting of chloroform/methanol/acetic acid/water (65/25/2/4, v/v/v/v) [16] and by CM-cellulose column chromatography [22]. The purified phospholipids were stored at –20 °C until use.

2.3. Acid hydrolysis of phospholipids

Phospholipids were hydrolyzed by boiling them in 1 ml of 6 M HCl for 6 h. The hydrolysate was mixed with 9 volumes of chloroform/methanol/water (27:13:5, v/v/v) and centrifuged at 100 × *g* for 20 min. The aqueous fraction containing amino acids was collected and stored at –20 °C until use.

2.4. Amino acid analysis

The aqueous fraction was applied to a Hitachi L-8500 amino acid analyzer (Hitachi Ltd., Tokyo, Japan). A buffer set (MCIBUFFER L-8500-PH KIT) was purchased from Wako (Osaka, Japan). Amino

acids were detected by on-line post column reaction with ninhydrin and were detected at 570 nm.

2.5. Derivatization of amino acids

Amino acids were derivatized using OPA and Boc-L-Cys according to the method described by Hashimoto et al. [23] (Scheme 1). The derivatization reagent was prepared daily by dissolving 10 mg of OPA and 10 mg of Boc-L-Cys in 1 ml of methanol. A borate buffer was made using 0.4 M boric acid adjusted to pH 9.0 with NaOH. A Boc-L-Cys-OPA reagent (100 μl) and the borate buffer (375 μl) were added to a plastic tube containing 25 μl of sample. After derivatization for 2 min at ambient temperature, an aliquot (20 μl) of the reaction mixture was introduced into the HPLC system.

2.6. HPLC–ESI-MS analysis

Boc-L-Cys-OPA amino acid derivatives were separated using an HPLC system (Shimadzu, Kyoto, Japan) equipped with a Cosmosil 5C₁₈-AR-II column (4.6 mm × 250 mm) operated at 0.8 ml/min at 20 °C with a linear gradient from 20% to 40% mobile phase B over a period of 20 min. Mobile phase A consisted of 0.1 M acetate buffer (pH 6.0), 7% acetonitrile, and 3% tetrahydrofuran (THF), and mobile phase B consisted of 0.1 M acetate buffer (pH 6.0), 47% acetonitrile, and 3% THF, according to previously described methods [23]. The flow rate of the eluent from the HPLC column was split into a ratio of 1:16 such that only 50 μl/min of the eluent entered the mass spectrometer. The mass spectrometric measurements were performed using an API 3000 triple quadrupole instrument (PE Sciex, Toronto, Canada). To measure the negative ion spectra, we set the ion spray voltage (IS), orifice voltage (OR), focusing ring voltage (RNG), and channel electron multiplier voltage (CEM) at –4.0 kV, –30 V, –200 V, and 2.2 kV, respectively. The instrument was calibrated using a polypropylene glycol solution. Nitrogen was used as the nebulizer gas, curtain gas, and collision gas. The data were acquired over the mass ranges of 421–424, 435–437, 450–454, and 463–467 *m/z*.

2.7. ESI-MS/MS analysis

Purified phospholipids in chloroform were dried under a stream of nitrogen gas and resuspended in acetonitrile/methanol (2/1, v/v) containing 0.1% ammonium formate (pH 6.5). The lipid solution was injected into the ESI-MS/MS system (PE Sciex, Toronto, Canada) and analyzed using the neutral loss scan and product ion scan modes. In both the scan modes, IS, OR, RNG, CEM, and collision energy were set at –5.0 kV, –80 V, –200 V, 2.8 kV, and 51 eV, respectively. A syringe infusion pump (Harvard Apparatus, Cambridge, MA) delivered solvent at 2.5 μl/min to the ESI probe. The lipid solution was

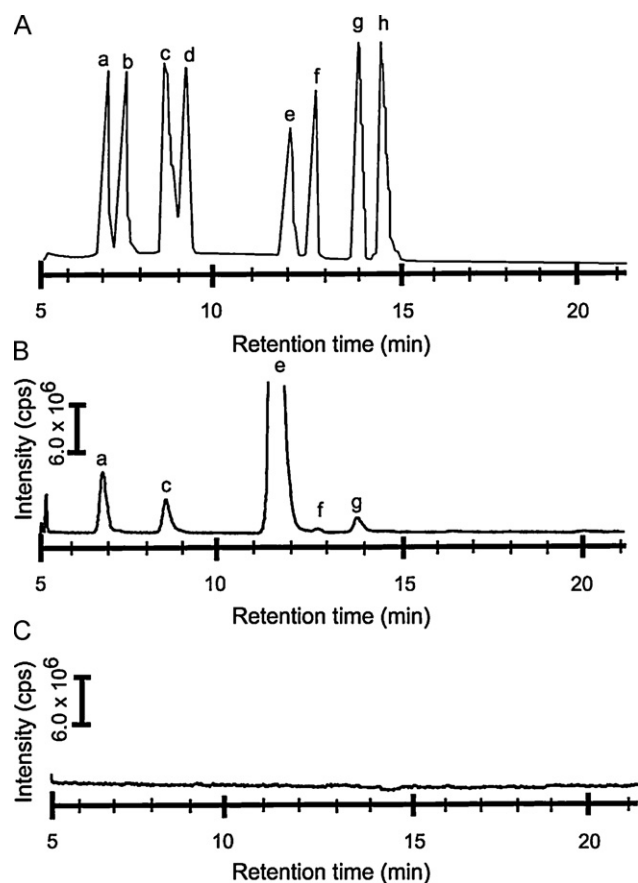


Fig. 1. HPLC-ESI-MS analysis of the acid-hydrolysates of lipids from porcine brain. (A) Typical chromatogram of authentic D, L-amino acid derivatives. (B) PS was hydrolyzed using 6 M HCl for 6 h. Free amino acids were isolated and derivatized using Boc-L-Cys and OPA. (C) PS was boiled in water instead of HCl. The aqueous fraction was isolated and applied to the derivatization procedure. Data were acquired over the mass ranges of 421–424, 435–437, 450–454, and 463–467 m/z . The molecular masses of serine, threonine, aspartate, and glutamate derivatives were 424, 438, 452, and 466 Da, respectively. The peaks of the Boc-L-Cys-OPA derivatives of L-aspartate, D-aspartate, L-glutamate, D-glutamate, L-serine, D-serine, L-threonine and D-threonine are indicated by a, b, c, d, e, f, g, h, respectively.

introduced using a 100- μ l glass syringe with a stainless steel needle (Hamilton Co., Reno, NV).

3. Results

3.1. Identification of amino acids in a hydrolysate of lipids from porcine cerebrum

To investigate whether amino acids other than serine can exist as the base moiety of phospholipids, lipids from porcine cerebrum were hydrolyzed with HCl. The hydrolysates were derivatized using OPA and Boc-L-Cys [23] and subjected to HPLC-ESI-MS analysis. Because the Boc-L-Cys-OPA derivative exists as diastereomers, the steric bulkiness of an L-amino acid derivative differs from that of the corresponding D-amino acid derivative. The reverse-phase ODS column is capable of separating compounds with different steric bulkiness as well as hydrophobicity. Therefore, the diastereoisomeric derivatization of amino acids with OPA and Boc-L-Cys has been used to determine the chirality of free amino acids. As shown in Fig. 1B, 3 peaks were detected at 6.86, 8.74, and 13.82 min in addition to those representing derivatives of D-serine (12.72 min) and L-serine (11.76 min). The m/z values of the peaks at 6.86, 8.74, and 13.82 min were 451, 465, and 437, respectively, which matched the m/z values of the Boc-L-Cys-OPA derivatives of authentic L-

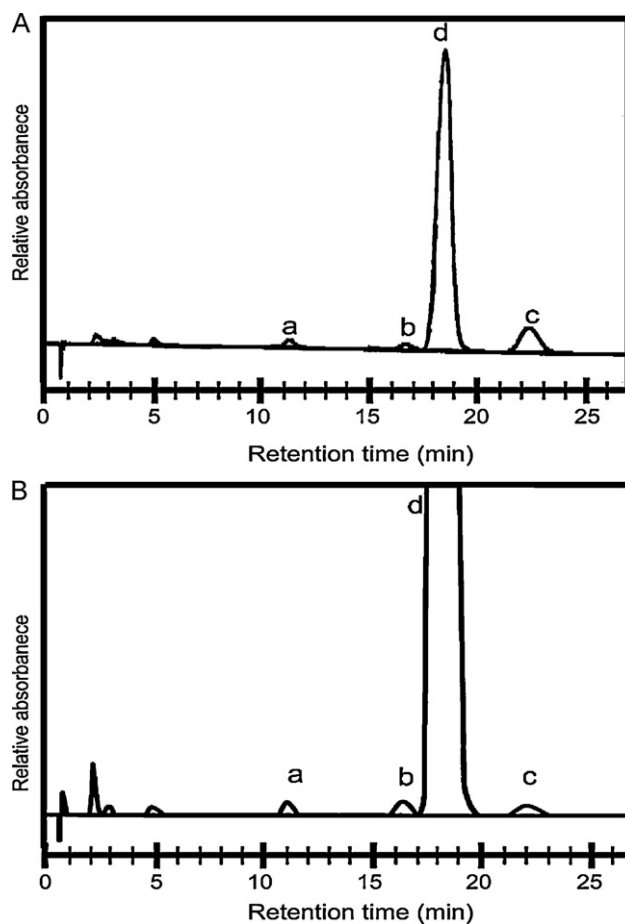


Fig. 2. Amino acid analysis of the acid-hydrolysates of lipids found in rat cerebrum and liver. A chromatogram of amino acids detected in a hydrolysate of rat liver phospholipids (A) and rat cerebrum phospholipids (B), which were purified by preparative TLC and CM-cellulose column chromatography, is shown. The peaks representing aspartate, threonine, glutamate, and serine are indicated by a, b, c, and d, respectively.

aspartate, L-glutamate, and L-threonine, respectively. The retention times of the 3 peaks were also consistent with those of the authentic derivatives of L-aspartate, L-glutamate, and L-threonine (Fig. 1A). The 3 peaks were not detected in the lipid samples that were boiled in water instead of HCl (Fig. 1C), and this finding confirmed that the lipid samples were not contaminated by free amino acids. These results suggest that L-aspartate, L-glutamate, and L-threonine occur as base moieties of phospholipids in porcine cerebrum.

3.2. Analysis of phospholipid hydrolysates from rat cerebrum and liver

To further examine whether aspartate, glutamate, and threonine can be liberated from phospholipids by hydrolysis, we extracted lipids from rat liver and isolated a PS-rich phospholipid fraction by using TLC and CM cellulose column chromatography. Because the mobility of PThr and PS is indistinguishable on TLC plates and CM cellulose columns [16], it was expected that the PS-rich phospholipid fraction would at least contain PThr. The purified PS-rich fraction was hydrolyzed by HCl and analyzed using an amino acid analyzer. As shown in Fig. 2A, peaks corresponding to not only serine and threonine but also aspartate and glutamate were detected. We also similarly analyzed the hydrolysate of a PS-rich fraction obtained from rat cerebrum and detected aspartate, glutamate, and threonine in addition to serine as the products of phospholipid hydrolysis (Fig. 2B). These results strongly suggest

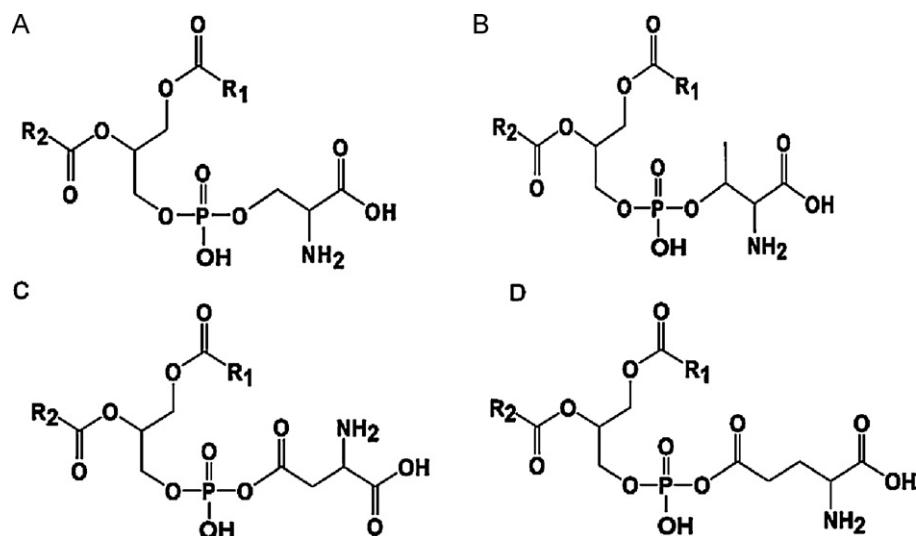


Fig. 3. Structures of PS, PThr, PAsp, and PGlu. The known structures of PS (A) and PThr (B) and the proposed structures of PAsp (C) and PGlu (D) are shown.

that not only serine and threonine but also aspartate and glutamate exist as acid-hydrolyzable moieties of phospholipids in the cerebrum and liver of rats. Our data also suggest that the mobility of phospholipids containing aspartate and glutamate is similar to that of PS and PThr under TLC and CM-cellulose column chromatography conditions.

3.3. ESI-MS/MS analyses of phospholipids from rat cerebrum

According to the results described above, if aspartate and glutamate are bound to phosphatidic acid to form carboxylate–phosphate anhydride, then phosphatidyl-L-aspartate (PAsp) and phosphatidyl-L-glutamate (PGlu) are expected to occur in rat tissues (Fig. 3). To confirm this hypothesis, we analyzed the phospholipids found in rat brain by performing fragmentation reactions of the polar head groups of phospholipids during ESI-MS/MS. Fragmentation reactions allow specific detection of a phospholipid species by neutral loss scanning. Through this technique, it was shown that PS and PThr can be selectively detected by a neutral loss of 87 Da [24,25] and 101 Da [26], respectively. Accordingly, when similar fragmentation reactions occur in PAsp and PGlu, it is expected that neutral losses of 115 Da and 129 Da, respectively, should be observed. As expected, our ESI-MS/MS analysis of phospholipids found in rat brain detected neutral loss peaks of 115 Da and 129 Da (Fig. 4B and C). The neutral loss peak of 101 Da, corresponding to PThr, was also detected (Fig. 4A). These data suggest that PAsp and PGlu as well as PThr do occur in fractions of rat brain phospholipids.

Furthermore, we performed product ion scanning of the following peaks, identified as major peaks by the neutral loss scan: m/z 802.7 and 848.7 corresponding to PThr (Fig. 5A and B), m/z 816.7 and 862.7 corresponding to PAsp (Fig. 5C and D), and m/z 830.3 and 876.8 corresponding to PGlu (Fig. 5E and F). The product ion scans detected several peaks that can be assigned to fatty acid fragments (Fig. 5). The fragments at m/z 281.5, 283.5, and 327.5 were identified as the anions of oleic acid, stearic acid, and docosahexaenoic acid (DHA), respectively. The fragment at m/z 153 was consistent with the 1,2-cyclic phosphodiester of glycerol, which is a product ion from every glycerophospholipid [24,25]. These results suggest the presence of PThr-(18:0, 18:1), PThr-(18:0, 22:6), PAsp-(18:0, 18:1), PAsp-(18:0, 22:6), PGlu-(18:0, 18:1), and PGlu-(18:0, 22:6) in rat brain.

4. Discussion

We previously showed that D-PS occurs in rat cerebrum and various other rat tissues. We also showed that free D-serine can be incorporated into PS in an *in vitro* system by using cerebrum extract, suggesting that D-PS is formed by a base-exchange reaction [12,13]. In mammals, free D-serine is distributed in the cerebrum [27,28] and plays an important role as a coagonist of the glycine site of N-methyl-D-aspartate (NMDA) receptors [29,30]. The intracellular D-serine levels are regulated by serine racemase [31,32] and D-amino acid oxidase with its effector pLG72 [33]. In addition, PS is an abundant component of membranes of brain cells, and thus, our previous results suggest that the synthesis and degradation of D-PS affect the intracellular D-serine levels, thereby modulating neurotransmission.

In this study, we found that amino acids other than D- and L-serine occur as the base moieties of phospholipids in porcine and rat brains. From our data, these amino acids were determined to be L-threonine, L-aspartate, and L-glutamate. L-Threonine, in addition to serine, possesses a hydroxyl group in its side chain and thus probably esterifies at the phosphoryl group of a *sn*-glycero-3-phosphate phospholipid backbone. In contrast, the side chains of L-aspartate and L-glutamate contain a carboxylate group. Therefore, we propose that these dicarboxylic amino acids form a carboxylate–phosphate anhydride bond with phosphatidic acid. To our knowledge, this is the first study that showed the presence of phospholipids with a carboxylate–phosphate anhydride bond. No other amino acids, except serine, threonine, aspartate, and glutamate, were detected in our HPLC-ESI-MS and amino acid analyses. Especially, hydroxyl-containing tyrosine and homoserine and reactive thiol-containing cysteine and homocysteine were not detected in the lipid hydrolysates. This finding indicates that PThr, PAsp, and PGlu are not nonspecific resultant products, which could have been indistinguishably formed by the base-exchange reactions of phospholipids. Instead, they are possibly synthesized by particular metabolic reactions. Although a wide variety of α -carboxyl group-containing amino acids exists, only L-aspartate and L-glutamate, in addition to L-threonine and L- and D-serine were found in the lipid hydrolysates. Therefore, we propose that the carboxylate–phosphate anhydride bond in PAsp and PGlu is formed between the phosphoryl group of a phospholipid and the distal carboxyl groups (i.e., β -carboxyl and γ -carboxyl) of L-aspartate and L-glutamate. The carboxylate–phosphate anhydride bond found in PAsp and PGlu may have a certain susceptibility of nucleophilic

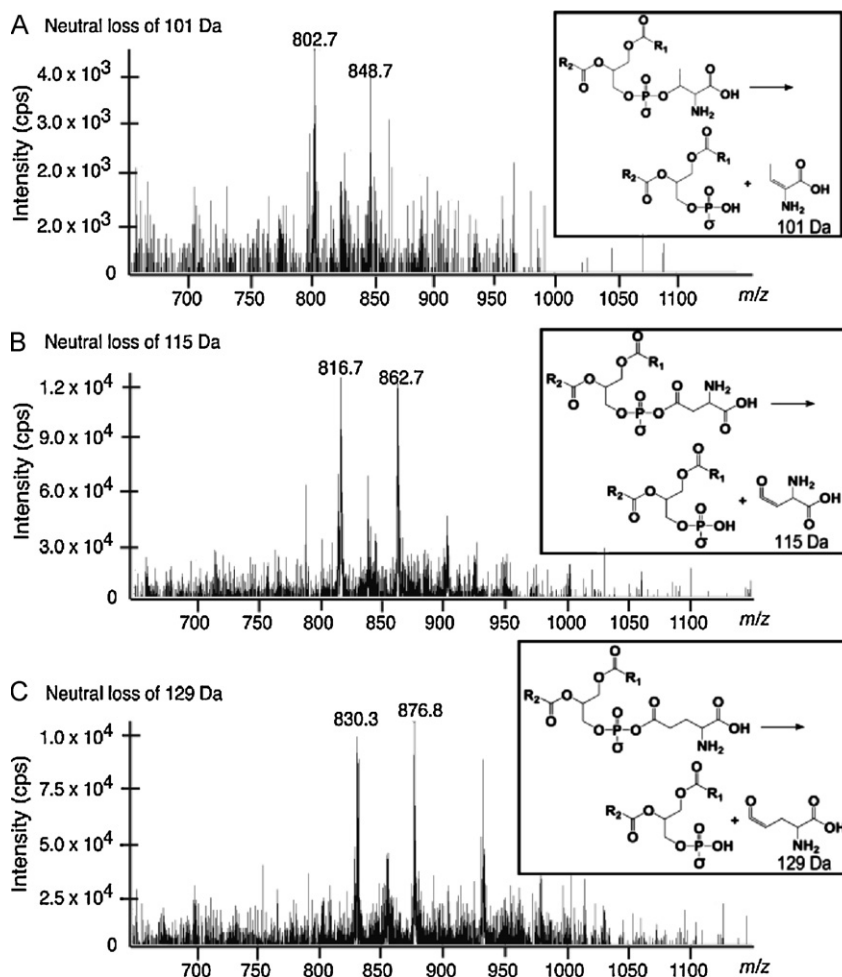


Fig. 4. ESI-MS/MS analysis with neutral loss scanning of the phospholipids detected in rat brain. Data of mass spectrometric analyses are shown: PThr with a neutral loss of 101 Da (A), PAsp with a neutral loss of 115 Da (B), and PGlu with a neutral loss of 129 Da (C). The inset of each panel shows the assumed fragmentation reaction in ESI-MS/MS.

attacks by nucleophiles existing in membranes. In the case of PGlu, pyroglutamate formation by intramolecular attack of Glu amino group to its carboxyl group may be plausible. Our results, however, suggest that PAsp and PGlu may be stabilized by as yet unknown mechanisms. Previous studies suggest that pK_a values of the amino and the carboxyl groups of PS are altered by the vicinal phospholipids around the PS and also by the forms of PS (vesicles, monolayers, etc.) [34,35]. Thus, a certain microenvironment, such as formation of a lipid raft-like complex, may prevent nucleophilic attacks of PAsp and PGlu in membranes. Our findings are supported by the chromatogram data previously reported by Mark-Malchoff et al. [36], which implies that PAsp and PGlu are not degraded during the general extraction and purification of phospholipids.

Unlike D-PS, D-aspartate was not found in the hydrolysate of phospholipids despite the fact that a considerable amount of D-aspartate occurs in various endocrine tissues [28,37,38] to regulate production and/or secretion of specific hormones [39,40]. However, this is not unexpected because Hashimoto et al. reported that significant considerable amount of free D-aspartate is not present in rat cerebrum at postnatal week 7 [28]. It will be interesting to analyze hydrolysates of phospholipids from testis, which contain relatively high concentrations of free D-aspartate [28], to examine the presence of phosphatidyl-D-aspartate.

It has already been reported that PThr occurs in several mammalian cells, fish, and eggs [14–17]. Although the physiological function of PThr remains unknown, its putative metabolic pathway has been suggested. It is thought that PThr can be synthesized by a

base-exchange enzyme that also catalyzes the synthesis of PS [17] and can be decarboxylated to yield phosphatidylisopropanolamine by PS decarboxylase [26]. It has been proposed that PThr is synthesized instead of PS when the intracellular levels of serine are insufficient for the synthesis of PS [17]. However, the results of the present study suggest that PThr appears to be constitutively present in both normal rat brain and normal porcine liver. This implies an as yet unknown biological role played by PThr in mammals.

On the other hand, the metabolic pathway of PAsp and PGlu remains unclear. There is no reported evidence that PS synthase or PS decarboxylase acts on phospholipids possessing a carboxylate-phosphate anhydride bond. This raises an interesting question about the metabolism of phospholipids. It is known that aspartate and glutamate act as neurotransmitters involved in learning and memory in mammalian brains [41,42]. Thus, PAsp and PGlu are potentially related to these neural processes through regulation of the brain levels of free aspartate and glutamate.

Our MS/MS analyses showed that PThr, PAsp, and PGlu each contain either a set of oleic acid and stearic acid or a set of oleic acid and DHA as the fatty acid moieties. Polyunsaturated fatty acids play essential roles in the development and function of the brain [43–45]. In particular, decreased levels of DHA in the brain and retina are associated with impairments in neural and visual functions [46–48]. PS contains a high proportion (>35%) of DHA as a fatty acid moiety [49]. It is thought that the developmental disorder of the central nervous system observed in fetal alcohol syndrome is partly due to a decreased level of DHA-containing PS [50–53].

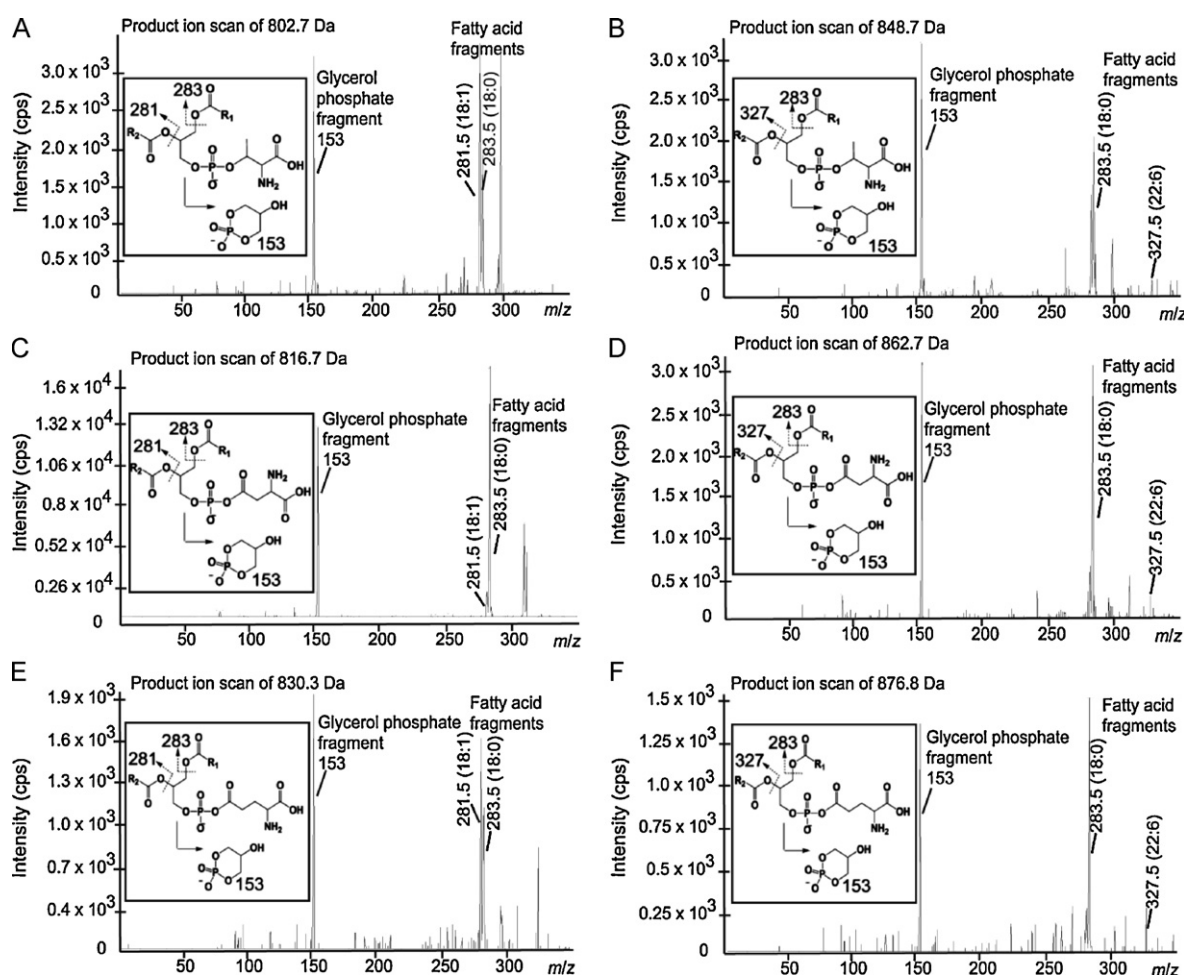


Fig. 5. ESI-MS/MS analysis with product ion scanning of the phospholipids found in rat brain. Product ion spectra of each $[M-H]^-$ ion, indicated in Fig. 3, with a molecular mass of 802.7 Da (A), 848.7 Da (B), 816.7 Da (C), 862.7 Da (D), 830.3 Da (E), and 876.8 Da (F), are shown. The peaks corresponding to a glycerol phosphate fragment, stearic acid (18:0), oleic acid (18:1), and docosahexaenoic acid (22:6) are also indicated.

Further studies are needed to investigate the potential biological roles played by the DHA-containing phospholipids discovered in this study.

It should be noted, however, that we identified the fatty acid composition of only two major molecular species from rat brain PThr, PAsp, and PGlu. However, in addition to stearic, oleic and docosahexaenoic acids, the brain phospholipids should contain palmitic and arachidonic acids as major ones. Therefore, more careful study is required to clarify the entire fatty acid composition of those phospholipids.

5. Conclusions

We investigated the base moieties of phospholipids found in rat brain and liver and porcine cerebrum by a combination of HPLC-ESI-MS analysis, amino acid analysis, and ESI-MS/MS analysis followed by neutral loss scanning and product ion scanning. Our data suggest the presence of PThr-(18:0, 18:1), PThr-(18:0, 22:6), PAsp-(18:0, 18:1), PAsp-(18:0, 22:6), PGlu-(18:0, 18:1), and PGlu-(18:0, 22:6) in mammalian tissues. This study is the first to identify naturally occurring phospholipids with carboxylate-phosphate anhydride bonds.

References

[1] V.A. Fadok, D.R. Voelker, P.A. Campbell, J.I. Cohen, D.L. Bratton, P.M. Henson, *J. Immunol.* 148 (1992) 2207.

[2] V.A. Fadok, A. de Cathelineau, D.L. Daleke, P.M. Henson, D.L. Bratton, *J. Biol. Chem.* 276 (2001) 1071.
 [3] M.O. Li, M.R. Sarkisian, W.Z. Mehal, P. Kacic, R.A. Flavell, *Science* 302 (2003) 1560.
 [4] K. Balasubramanian, B. Mirnikjoo, A.J. Schroit, *J. Biol. Chem.* 282 (2007) 18357.
 [5] Y. Nishizuka, *Nature* 308 (1984) 693.
 [6] R.M. Bell, D.J. Burns, *J. Biol. Chem.* 266 (1991) 4661.
 [7] Y. Nishizuka, *Science* 258 (1992) 607.
 [8] L. Bittova, R.V. Stahelin, W. Cho, *J. Biol. Chem.* 276 (2001) 4218.
 [9] J. Folch, H.A. Schneider, *J. Biol. Chem.* 137 (1941) 51.
 [10] J. Folch, *J. Biol. Chem.* 139 (1941) 973.
 [11] J. Folch, *J. Biol. Chem.* 174 (1947) 439.
 [12] T. Omori, H. Mihara, T. Kurihara, N. Esaki, *Biochem. Biophys. Res. Commun.* 382 (2009) 415.
 [13] T. Omori, H. Mihara, T. Kurihara, N. Esaki, *Biosci. Biotechnol. Biochem.* 74 (2010) 1953.
 [14] D.N. Rhodes, C.H. Lea, *Biochem. J.* 65 (1957) 526.
 [15] H. Igarashi, K. Zama, M. Katada, *Nature* 181 (1958) 1282.
 [16] D. Mark-Malchoff, G.V. Marinetti, G.D. Hare, A. Meisler, *Biochemistry* 17 (1978) 2684.
 [17] J. Mitoma, T. Kasama, S. Furuya, Y. Hirabayashi, *J. Biol. Chem.* 273 (1998) 19363.
 [18] O. Kuge, M. Nishijima, Y. Akamatsu, *J. Biol. Chem.* 266 (1991) 24184.
 [19] O. Kuge, K. Saito, M. Nishijima, *J. Biol. Chem.* 272 (1997) 19133.
 [20] J.E. Vance, R. Steenbergen, *Prog. Lipid Res.* 44 (2005) 207.
 [21] J. Folch, I. Ascoli, M. Lees, J.A. Meath, N. Le Baron, *J. Biol. Chem.* 191 (1951) 833.
 [22] P. Comfurius, R.F. Zwaal, *Biochim. Biophys. Acta* 488 (1977) 36.
 [23] A. Hashimoto, T. Nishikawa, T. Oka, K. Takahashi, T. Hayashi, *J. Chromatogr.* 582 (1992) 41.
 [24] B. Brugger, G. Erben, R. Sandhoff, F.T. Wieland, W.D. Lehmann, *Proc. Natl. Acad. Sci. U. S. A.* 94 (1997) 2339.
 [25] M. Pulfer, R.C. Murphy, *Mass Spectrom. Rev.* 22 (2003) 332.
 [26] L. Heikinheimo, P. Somerharju, *Traffic* 3 (2002) 367.
 [27] A. Hashimoto, T. Nishikawa, T. Hayashi, N. Fujii, K. Harada, T. Oka, K. Takahashi, *FEBS Lett.* 296 (1992) 33.
 [28] A. Hashimoto, T. Oka, T. Nishikawa, *Eur. J. Neurosci.* 7 (1995) 1657.

- [29] A. Hashimoto, T. Nishijima, T. Oka, K. Takahashi, *J. Neurochem.* 60 (1993) 783.
- [30] M.J. Schell, M.E. Molliver, S.H. Snyder, *Proc. Natl. Acad. Sci. U. S. A.* 92 (1995) 3948.
- [31] H. Wolosker, K.N. Sheth, M. Takahashi, J.P. Mothet, R.O. Brady Jr., C.D. Ferris, S.H. Snyder, *Proc. Natl. Acad. Sci. U. S. A.* 96 (1999) 721.
- [32] V.N. Foltyn, I. Bendikov, J. De Miranda, R. Panizzutti, E. Dumin, M. Shleper, P. Li, M.D. Toney, E. Kartvelishvily, H. Wolosker, *J. Biol. Chem.* 280 (2005) 1754.
- [33] S. Sacchi, M. Bernasconi, M. Martineau, J.P. Mothet, M. Ruzzene, M.S. Pilone, L. Pollegioni, G. Molla, *J. Biol. Chem.* 283 (2008) 22244.
- [34] F.C. Tsui, D.M. Ojcius, W.L. Hubbell, *Biophys. J.* 49 (1986) 459.
- [35] M.R. Moncelli, L. Becucci, R. Guidelli, *Biophys. J.* 66 (1994) 1969.
- [36] D. Mark-Malchoff, G.V. Marinetti, J.D. Hare, A. Meisler, *Biochem. Biophys. Res. Commun.* 75 (1977) 589.
- [37] K. Imai, T. Fukushima, T. Oka, K. Takahashi, *Biomed. Chromatogr.* 9 (1995) 106.
- [38] T. Furuchi, H. Homma, *Biol. Pharm. Bull.* 28 (2005) 1566.
- [39] Y. Takigawa, H. Homma, J.A. Lee, T. Fukushima, T. Santa, T. Iwatsubo, K. Imai, *Biochem. Biophys. Res. Commun.* 248 (1998) 641.
- [40] Y. Nagata, H. Homma, J.A. Lee, K. Imai, *FEBS Lett.* 444 (1999) 160.
- [41] P.R. Maycox, J.W. Hell, R. Jahn, *Trends Neurosci.* 13 (1990) 83.
- [42] T. Miyaji, N. Echigo, M. Hiasa, S. Senoh, H. Omote, Y. Moriyama, *Proc. Natl. Acad. Sci. U. S. A.* 105 (2008) 11720.
- [43] M. Vreugdenhil, C. Bruehl, R.A. Voskuyl, J.X. Kang, A. Leaf, W.J. Wadman, *Proc. Natl. Acad. Sci. U. S. A.* 93 (1996) 12559.
- [44] K. Kitajka, L.G. Puskas, A. Zvara, L. Hackler Jr., G. Barcelo-Coblijn, Y.K. Yeo, T. Farkas, *Proc. Natl. Acad. Sci. U. S. A.* 99 (2002) 2619.
- [45] K. Kitajka, A.J. Sinclair, R.S. Weisinger, H.S. Weisinger, M. Mathai, A.P. Jaysooriya, J.E. Halver, L.G. Puskas, *Proc. Natl. Acad. Sci. U. S. A.* 101 (2004) 10931.
- [46] R. Uauy, D.R. Hoffman, P. Peirano, D.G. Birch, E.E. Birch, *Lipids* 36 (2001) 885.
- [47] J. Catalan, T. Moriguchi, B. Slotnick, M. Murthy, R.S. Greiner, N. Salem Jr., *Behav. Neurosci.* 116 (2002) 1022.
- [48] L.G. Puskas, E. Bereczki, M. Santha, L. Vigh, G. Csanadi, F. Spener, P. Ferdinandy, A. Onochy, K. Kitajka, *Biochimie* 86 (2004) 817.
- [49] R. Hitzemann, *Neurochem. Res.* 6 (1981) 935.
- [50] P.S. Sastry, *Prog. Lipid Res.* 24 (1985) 69.
- [51] R.A. Harris, D.M. Baxter, M.A. Mitchell, R.J. Hitzemann, *Mol. Pharmacol.* 25 (1984) 401.
- [52] Z. Wen, H.Y. Kim, *J. Neurochem.* 89 (2004) 1368.
- [53] Z. Wen, H.Y. Kim, *J. Neurosci. Res.* 85 (2007) 1568.