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Diacylglycerol Kinase δ Phosphorylates Phosphatidylcholine-specific Phospholipase C-dependent, Palmitic Acid-containing Diacylglycerol Species in Response to High Glucose Levels*

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Background: Diacylglycerol (DG) kinase (DGK) δ is activated by acute high glucose stimulation.
Results: DGKδ high glucose-dependently phosphorylates 30:0-, 32:0-, and 34:0-DG and interacts with phosphatidylcholine-specific phospholipase C (PC-PLC).
Conclusion: DGKδ utilizes palmitic acid-containing DG species and metabolically connects with PC-PLC.
Significance: The newly identified PC-PLC/DGKδ pathway could play an important role in insulin signaling and glucose uptake.

Decreased expression of diacylglycerol (DG) kinase (DGK) δ in skeletal muscles is closely related to the pathogenesis of type 2 diabetes. To identify DG species that are phosphorylated by DGKδ in response to high glucose stimulation, we investigated high glucose-dependent changes in phosphatidic acid (PA) molecular species in mouse C2C12 myoblasts using a newly established liquid chromatography/MS method. We found that the suppression of DGKδ2 expression by DGKδ-specific siRNAs significantly inhibited glucose-dependent increases in 30:0-, 32:0-, and 34:0-PA and moderately attenuated 30:1-, 32:1-, and 34:1-PA. Moreover, overexpression of DGKδ2 also enhanced the production of these PA species. MS/MS analysis revealed that these PA species commonly contain palmitic acid (16:0). D609, an inhibitor of phosphatidylcholine-specific phospholipase C (PC-PLC), significantly inhibited the glucose-stimulated production of the palmitic acid-containing PA species. Moreover, PC-PLC was co-immunoprecipitated with DGKδ2. These results strongly suggest that DGKδ preferably metabolizes palmitic acid-containing DG species supplied from the PC-PLC pathway, but not arachidonic acid (20:4)-containing DG species derived from the phosphatidylinositol turnover, in response to high glucose levels.

Type 2 diabetes is expected to afflict over 300 million people worldwide by 2015 (1). The characteristic features of type 2 diabetes include insulin resistance, glucose intolerance, hyperglycemia, and often, hyperinsulinemia (2). Glucose-induced insulin resistance is associated with a temporal increase in the intracellular diacylglycerol (DG)[2] mass in skeletal muscle (3).

DG is metabolized, at least in part, by DG kinase (DGK), which phosphorylates DG to generate phosphatidic acid (PA) (4–8). To date, 10 mammalian DGK isozymes (α, β, γ, δ, η, κ, ε, ζ, ι, and θ) have been identified, and these isozymes are subdivided into five groups according to their structural features (6, 7). Type II DGKs consist of the δ, η, and κ isoforms (9, 10). Moreover, alternatively spliced forms of DGKδ (δ1 and δ2) (11) and η (η1 and η2) (12) have been found.

DGKδ is highly expressed in skeletal muscle (13), which is a major insulin-target organ for glucose disposal (14). Chibalin *et al.* (15) demonstrated that DGKδ regulates glucose uptake and that a decrease in DGKδ expression resulted in the aggravation of type 2 diabetes. Long term exposure (96 h) to high glucose medium decreased DGKδ protein levels in primary cultured skeletal muscle cells, and the transcription of DGKδ and the levels of DGKδ protein were also reduced in skeletal muscles from type 2 diabetes patients (15). Moreover, DGKδ haploinsufficient mice ($DGK\delta^{+/-}$) exhibited decreased total DGK activity, reduced DGKδ protein levels, and the accumulation of DG in skeletal muscle. The increase in the amount of DG caused the increase in the phosphorylation of protein kinase C (PKC) δ and a reduction in the expression of the insulin receptor and insulin receptor substrate-1 proteins involved in insulin signaling (15). Furthermore, Miele *et al.* (16) reported that acute high glucose exposure (within 5 min) increased DGKδ activity in skeletal muscle cells followed by a reduction of PKCα activity and transactivation of the insulin receptor signal.

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[2] The abbreviations used are: DG, diacylglycerol; DGK, DG kinase; D609, *O*-tricyclo[5.2.1.0^{2,6}]dec-9-yl dithiocarbonate; FIPI, 5-fluoro-2-indolyl deschlorohalopemide; ESI, electrospray ionization; PA, phosphatidic acid; PC, phosphatidylcholine; PC-PLC, PC-specific phospholipase C; PLD, phospholipase D; TOFA, 5-(tetradecyloxy)-2-furoic acid; PI, phosphatidylinositol; DMSO, dimethyl sulfoxide; AcGFP, GFP from *Aequorea coerulescens*.

Hence, these studies indicate that DG consumed by DGKδ in response to high glucose exposure is a key regulator of glucose uptake in skeletal muscle cells. DGKδ1 translocated from the cytoplasm to the plasma membrane in mouse myoblast C2C12 cells within 5 min of short term exposure to a high glucose concentration, whereas DGKδ2 was located in punctate vesicles irrespective of the glucose concentration (17).

Mammalian cells contain at least 50 structurally distinct molecular DG species because DG contains a variety of fatty acyl moieties at positions 1 and 2 (18). In general, DGs containing arachidonic acid (20:4), especially 18:0/20:4-DG (38:4-DG), in the phosphatidylinositol (PI) turnover are important molecules that serve as second messengers for PKC activation (18). Moreover, previous studies have demonstrated that DGKϵ preferably phosphorylates arachidonic acid-containing DGs derived from PI turnover (19, 20). Therefore, it is generally believed that all DGKs preferentially metabolize 38:4-DG for the regulation of signal transduction. However, the DG molecular species phosphorylated by DGKδ in response to glucose stimulation remain unknown.

In this study, we investigated the changes in the amounts of PA molecular species that are produced by DGK in glucose-stimulated C2C12 myoblasts using our previously developed liquid chromatography/electrospray ionization mass spectrometry (LC/ESI-MS) method (21) to identify the DG molecular species metabolized by DGKδ under short term high glucose conditions. Interestingly, the LC/ESI-MS analyses indicated that DGKδ preferably metabolizes limited DG molecular species, 30:0-, 30:1-, 32:0-, 32:1-, 34:0-, and 34:1-DG, commonly containing palmitic acid (16:0), but not DG species containing arachidonic acid in response to high glucose stimulation. Moreover, the 30:0-, 32:0-, and 34:0-DG species were suggested to be supplied by phospholipase C (PLC)-dependent phosphatidylcholine (PC) hydrolysis, indicating an unexpected linkage between PC-PLC and DGKδ.

EXPERIMENTAL PROCEDURES

Cell Culture—C2C12 mouse myoblasts were maintained on 100-mm dishes in DMEM (Wako Pure Chemicals) containing 10% FBS (Biological Industries-Invitrogen) at 37 °C in an atmosphere containing 5% CO_2. For differentiation to myotubes, confluent C2C12 myoblasts were cultured in differentiation medium (DMEM containing 0.1% FBS and 5 μg/ml insulin (Sigma-Aldrich)) for 4 days.

Establishment of a Stable Cell Line Overexpressing DGKδ—To establish C2C12 cells stably expressing human DGKδ2, the cells were transfected with pAcGFP-DGKδ2 (11, 17) using PolyFect (Qiagen) according to the instruction manual and were selected with 800 μg/ml G418 for 2 weeks. Single colonies were isolated and then were then grown in DMEM containing 10% FBS.

RNA Interference—To silence the expression of mouse DGKδ, the following Stealth RNAi duplexes (Invitrogen) were used: DGKδ-siRNA-1, 5′-GAAUGUGAUGCUGGAUCUUACUAAA-3′ and 5′-UUUAGUAAGAUCCAGCAUCACAUUC-3′; DGKδ-siRNA-2, 5′-UGGCAUUGGCUUGGAUGCAAAGAUA-3′ and 5′-UAUCUUUGCAUCCAAGCCAAUGCCA-3′. The duplexes were transfected into C2C12 myoblasts by electroporation (at 350 V and 300 microfarads) using the Gene Pulser Xcell™ electroporation system (Bio-Rad Laboratories). The transfected cells were then allowed to grow for 48 h in DMEM containing 10% FBS.

Glucose Stimulation and Treatment with Lipid Metabolism Enzyme Inhibitors—Glucose stimulation was performed as reported previously (16). Briefly, untransfected C2C12 myoblasts and C2C12 myoblasts transfected with Stealth RNAi duplexes were grown on poly-L-lysine (Sigma-Aldrich)-coated culture dishes. The cells were rinsed and incubated in glucose-free medium (16) in the absence or presence of PC-PLC inhibitor *O*-tricyclo[5.2.1.$0^{2,6}$]dec-9-yl dithiocarbonate (D609, 100 μM, Calbiochem) (22), acetyl-CoA carboxylase inhibitor 5-(tetradecyloxy)-2-furoic acid (TOFA, 20 μM, Calbiochem) (23, 24), or phospholipase D (PLD) inhibitor 5-fluoro-2-indolyl deschlorohalopemide (FIPI, 100 nM, Calbiochem) (25) for 3 h. The cells were incubated for 5 min in the same buffer supplemented with 25 mM glucose.

Lipid Extraction and Western Blot Analysis—The cells grown under each culture condition were harvested and lysed in ice-cold lysis buffer (50 mM HEPES, pH 7.2, 150 mM NaCl, 5 mM $MgCl_2$, 1 mM dithiothreitol, cOmplete™ EDTA-free protease inhibitor (Roche Diagnostics)) followed by centrifugation at 1,000 × *g* for 5 min at 4 °C. Total lipids were extracted from the cell lysates (1.0 mg of protein), in which DGKδ expression was confirmed by Western blot analysis using an anti-DGKδ antibody (13), according to the method of Bligh and Dyer (26). The extracted lipids were used for subsequent MS analyses.

Analysis of PA Molecular Species—PAs in extracted cellular lipids (5 μl) containing 40 pmol of the 14:0/14:0-PA internal standard (Sigma-Aldrich) were analyzed separately by LC/ESI-MS using an Accela LC system (Thermo Fisher Scientific) coupled online to an Exactive Orbitrap MS (Thermo Fisher Scientific) equipped with an ESI source as described previously (21). The MS peaks are presented in the form of *X*:*Y*, where *X* is the total number of carbon atoms and *Y* is the total number of double bonds in both acyl chains of the PA.

For the identification of fatty acid residues in PA molecular species by ESI-MS/MS, PA molecular species (28:0 – 40:0-PA) were fractionated using the above LC/ESI-MS system equipped with an FC 203B fraction collector (Gilson). The mixture of these isolated PA molecular species was infused into an Exactive Orbitrap MS (Thermo Fisher Scientific) equipped with a syringe pump (an infusion rate of 5 μl/min) and an ESI source. A collision energy of 40 eV was used to obtain fragment ions.

Analysis of DG Molecular Species—The isolation of DG was performed according to previously reported procedures (27). The extracted cellular lipids (per 1 mg of protein) were developed on Silica Gel 60 high performance thin layer chromatography plates (Merck, 10 × 20 cm) using hexane/diethyl ether/acetic acid (75:25:1, v/v). After development, DG was extracted from silica gel and redissolved in 200 μl of methanol:chloroform (9:1, v/v) containing 1 μg/ml 12:0/12:0-DG (Avanti Polar Lipids), and 10 μl of 100 mM sodium acetate were added to each sample (28). MS analysis was performed on an Exactive Orbitrap MS (Thermo Fisher Scientific) equipped with a Fusion 100T syringe pump (an infusion rate of 5 μl/min, Thermo Fisher Scientific) and an ESI source. The ion spray

voltage was set to 5 kV in the positive ion mode. The capillary temperature was set to 300 °C.

Measurement of DGKδ Activity—The octyl glucoside-mixed micellar assay of DGK activity was performed as described previously (12). COS-7 cells transfected with p3×FLAG-DGKδ2 (29) were harvested and lysed in ice-cold lysis buffer followed by centrifugation at 1,000 × *g* for 5 min at 4 °C. The cell lysates were added to octyl glucoside buffer containing 2 mM 16:0/16:0-, 16:0/18:1-, or 18:0/20:4-DG (Avanti Polar Lipids) and 10 mM phosphatidylserine (Avanti Polar Lipids).

Immunoprecipitation and Measurement of PC-PLC Activity—The glucose-stimulated cells stably expressing human DGKδ2 were harvested and lysed in ice-cold lysis buffer (50 mM HEPES, pH7.2, 150 mM NaCl, 5 mM $MgCl_2$, 1% Nonidet P-40, 1 mM dithiothreitol, cOmplete™ EDTA-free protease inhibitor (Roche Diagnostics)) for immunoprecipitation. The mixtures were centrifuged at 12,000 × *g* for 5 min at 4 °C to yield the cell lysates. 500 μg of the cell lysates were incubated with normal rabbit IgG (2 μg, Santa Cruz Biotechnology) or rabbit anti-DGKδ antibody (2 μg) (13, 29) at 4 °C overnight and incubated with protein A/G PLUS-agarose (Santa Cruz Biotechnology) for an additional 1 h. The bead-bound proteins were washed with ice-cold wash buffer (50 mM HEPES, pH 7.2, 100 mM NaCl, 5 mM $MgCl_2$, 0.1% Triton X-100, 10% glycerol, 20 mM NaF) four times and resolved in 70 μl of 1× reaction buffer (50 mM Tris-HCl, pH 7.4, 140 mM NaCl, 10 mM dimethylglutarate, 2 mM $CaCl_2$) in the Amplex Red® PC-PLC assay kit (Molecular Probes-Life Technologies). In this enzyme-coupled assay, PC-PLC activity is monitored indirectly using 10-acetyl-3,7-dihydroxyphenoxazine (Amplex Red® reagent), a sensitive fluorogenic probe for H_2O_2. First, PC-PLC converts PC to form phosphocholine and DG. After the action of alkaline phosphatase, which hydrolyzes phosphocholine, choline is oxidized by choline oxidase to betaine and H_2O_2. Finally, H_2O_2, in the presence of horseradish peroxidase, reacts with Amplex Red® reagent in a 1:1 stoichiometry to generate the highly fluorescent product, resorufin. Resorufin has absorption and fluorescence emission maxima of ~571 nm and 585 nm, respectively. 50-μl aliquots of the mixtures were used for the measurement of PC-PLC activities, and 10 μl of the mixtures were used for Western blot analysis.

Statistics—All LC/ESI-MS data were normalized based on the protein content and the intensity of the internal standard. The data were represented as the mean ± S.D. Statistical analysis was performed using the two-tailed *t* test or analysis of variance followed by Tukey's post hoc test.

RESULTS

Increase in the Amount of PA by Acute Stimulation with High Glucose—We first examined whether the amount of total PA was increased in C2C12 myoblasts stimulated with 25 mM glucose. As shown in Fig. 1*A*, LC/ESI-MS analysis indicated that exposure to high glucose levels (for 5 min) statistically increased the total PA amounts (1.23-fold, $p < 0.005$). In addition, the stimulation significantly increased the amounts of C30 to C36 PA molecular species, with the exception of 36:1-PA (Fig. 1*B*). However, the stimulation did not substantially affect the production of C38 to C40 PA molecular species, including 38:4-PA, with the exception of 38:6-PA.

We investigated the high glucose-dependent increases of total PA amount and PA molecular species in C2C12 myoblasts at different time points. After 5 min of glucose stimulation, the levels of total PA and PA molecular species were significantly increased (Fig. 1, *C* and *D*). However, total PA and PA molecular species levels returned close to basal levels by prolonging the incubation with high glucose concentrations for up to 15 and 30 min. We confirmed that DGK activity *in vitro* was increased by glucose stimulation for 5 min (data not shown). These results strongly suggest that C2C12 myoblasts and L6 myotubes (16) have essentially the same lipid metabolism pathway to produce PA in response to acute glucose stimulation.

We confirmed the changes in the amounts of PA molecular species in C2C12 myotubes in response to acute high glucose stimulation (5 min). The glucose-stimulated C2C12 myotubes showed essentially the same results (Fig. 1, *E* and *F*) as those obtained with C2C12 myoblasts (Fig. 1, *A* and *B*). The results support that C2C12 myoblasts and myotubes possess essentially the same lipid metabolism pathway to produce PA in response to high glucose stimulation. Because C2C12 myoblasts were more efficiently transfected with siRNAs than C2C12 myotubes, C2C12 myoblasts were used for identification of PA molecular species produced by DGKδ in response to high glucose stimulation.

Effects of DGKδ-specific siRNAs on High Glucose-induced Increases in PA Molecular Species—To clarify whether the glucose-stimulated production of PA molecular species is catalyzed by DGKδ, we investigated the effects of a DGKδ-specific siRNA, DGKδ-siRNA-1. Of the two alternatively spliced DGKδ products, DGKδ1 and DGKδ2 (11), C2C12 myoblasts predominantly expressed DGKδ2 (Fig. 2*A*). DGKδ-siRNA-1 efficiently suppressed DGKδ2 expression in C2C12 myoblasts (Fig. 2*A*). To facilitate comparison, averages of the relative values (+glucose *versus* −glucose) from four independent experiments are displayed (Fig. 2*B*). Interestingly, the suppression of DGKδ expression by DGKδ-siRNA-1 significantly inhibited the glucose stimulation-dependent production of saturated fatty acid-containing C30-C34 PA species, 30:0-, 32:0-, and 34:0-PA, to their basal levels. In addition, one saturated and one monounsaturated fatty acid-containing PA, 34:1-PA, decreased as well. However, the amount of arachidonic acid (20:4)-containing PA, 38:4-PA, was not markedly changed (Fig. 2*B*). To rule out off-target effects of DGKδ-siRNA-1, we employed an independent siRNA targeted to a different region of DGKδ mRNA (DGKδ-siRNA-2). DGKδ-siRNA-2, which suppressed DGKδ2 expression slightly less strongly than DGKδ-siRNA-1 (Fig. 2*C*), also statistically inhibited the production of 30:0-, 34:1-, and 34:0-PA and moderately attenuated 32:0-PA generation (Fig. 2*D*). These results suggest that DGKδ selectively phosphorylated 30:0-, 32:0-, 34:1-, and 34:0-DG, which contain either two saturated fatty acids or one saturated and one monounsaturated fatty acids, but not 38:4-PA.

We investigated whether the decreases in the amounts of 30:0-, 32:0-, 34:1-, and 34:0-PA by DGKδ-siRNAs were due to decreases in the substrates, the corresponding DG species, in high glucose-stimulated and -unstimulated C2C12 myoblasts.

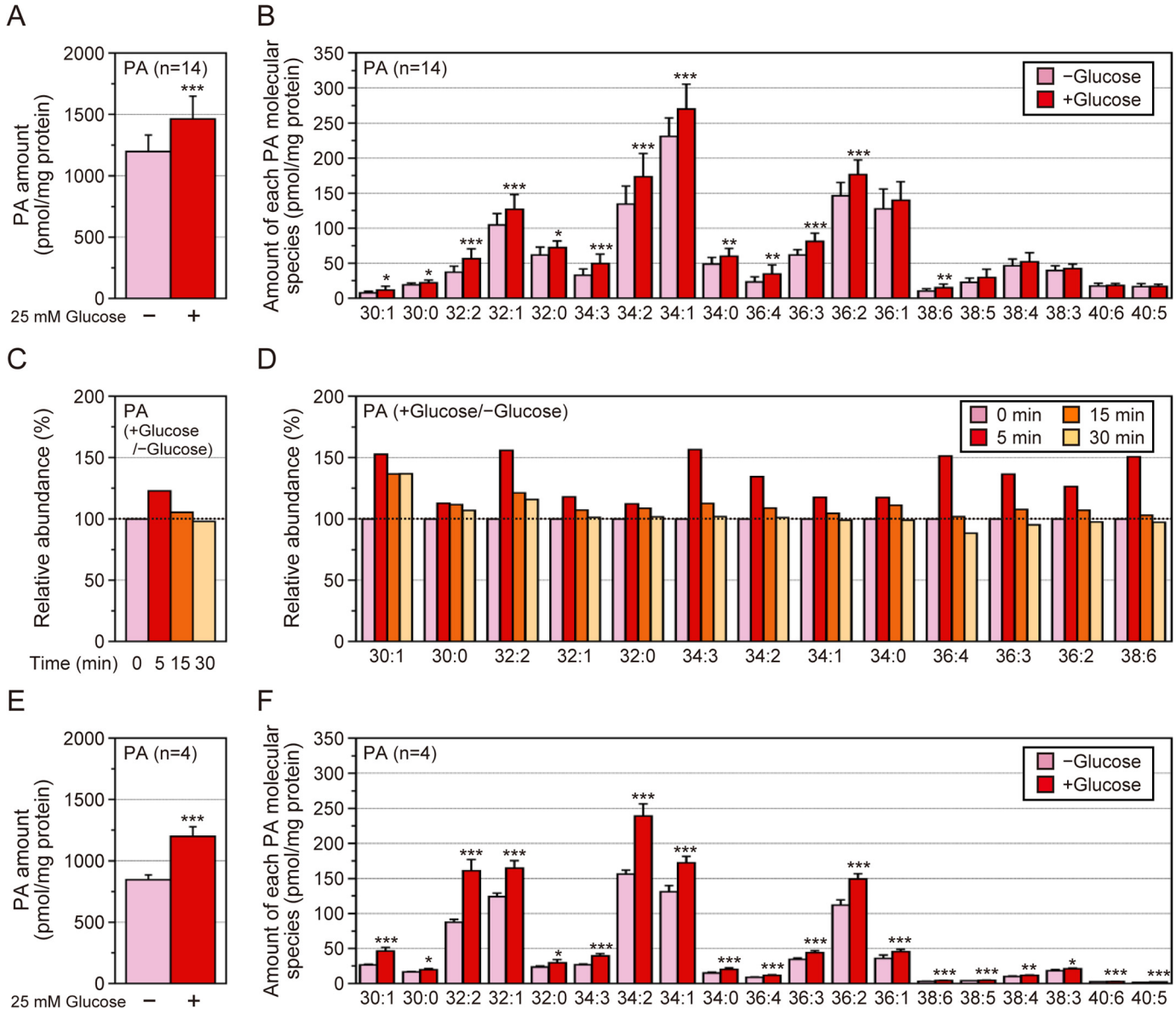

FIGURE 1. **Changes in the total PA and PA molecular species by high glucose stimulation in C2C12 myoblasts and myotubes.** *A* and *B*, the amounts of the total PAs (*A*) and major PA molecular species (*B*) in the glucose-unstimulated or glucose-stimulated C2C12 myoblasts were quantified using the LC/ESI-MS method. The values are presented as the mean ± S.D. ($n = 14$). *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.005$ (no stimulation *versus* glucose stimulation). *C* and *D*, the amounts of the total PAs (*C*) and major PA molecular species (*D*) that statistically increased in *A* in the cells stimulated by glucose for 5, 15, or 30 min were detected using the LC/ESI-MS method. The results are presented as the percentage of the value of PA molecular species in glucose-unstimulated cells. The values are presented as the mean ($n = 2$). Essentially the same results were obtained in two independent experiments. *E* and *F*, the amounts of the total PAs (*E*) and major PA molecular species (*F*) in the glucose-unstimulated or glucose-stimulated C2C12 myotubes were quantified using the LC/ESI-MS method. The values are presented as the mean ± S.D. ($n = 4$). *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.005$ (no stimulation *versus* glucose stimulation).

Glucose stimulation substantially increased the amounts of various DG species (Fig. 3). However, DGKδ-siRNA-1 failed to significantly affect the amounts of 30:0-, 32:0-, 34:1-, and 34:0-DG molecular species both in the absence and in the presence of high glucose levels. Therefore, it is likely that the decreases in the amounts of 30:0-, 32:0-, 34:1-, and 34:0-PA were not caused by decreased amounts of the corresponding DG species.

Effect of Overexpression of DGKδ on the Production of PA Molecular Species—To confirm the results of the siRNA experiments, we evaluated the result of DGKδ2 overexpression on high glucose-dependent production of PA species in C2C12 cells. In response to high glucose, the levels of 30:0-, 32:0-, and 34:0-PA statistically increased in C2C12 cells stably expressing DGKδ2 when compared with control cells (Fig. 4*B*). Moreover, 30:1- and 32:1-PA were also augmented. In contrast, 38:4-PA did not increase. Taken together with the siRNA results (Figs. 2 and 4), these results support the hypothesis that DGKδ phosphorylated DG species with an apparent preference for 30:0-, 32:0-, and 34:0-DG, but not arachidonic acid-containing DG, 38:4-DG. Moreover, it is possible that this enzyme also generates 30:1-, 32:1-, and 34:1-PA.

Fatty Acid Composition of 30:0-, 32:0-, and 34:0-PA—We next determined the molecular identities of the two fatty acids included in 30:0-, 32:0-, and 34:0-PA, which were indicated to be selectively generated by DGKδ2 in C2C12 cells. ESI-MS/MS

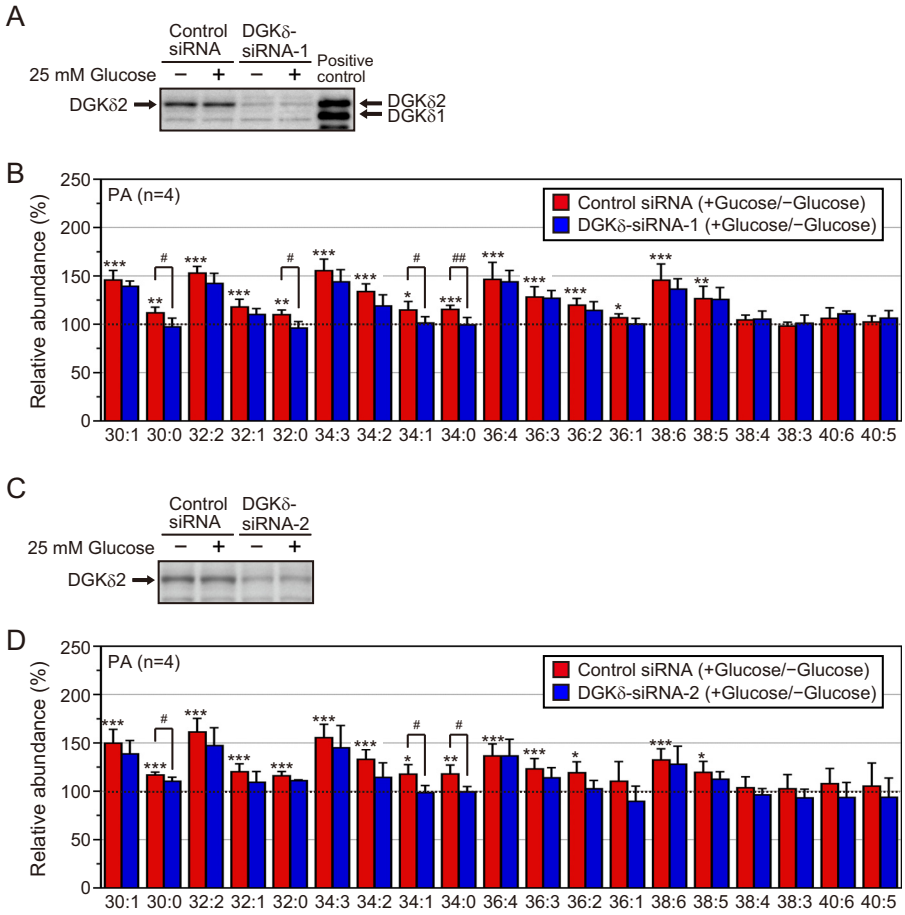

FIGURE 2. **Effects of DGKδ-siRNA-1 and -2 on high glucose-induced increases of PA molecular species in C2C12 myoblasts.** *A* and *C*, the suppression of DGKδ2 expression by DGKδ-siRNA-1 (*A*) or DGKδ-siRNA-2 (*C*) was confirmed by Western blot analysis using the anti-DGKδ antibody. Human DGKδ1 and DGKδ2 (11) expressed in COS-7 cells were electrophoresed as a control (*A*). *B* and *D*, the major PA molecular species in the glucose-unstimulated or glucose-stimulated cells transfected with control siRNA or DGKδ-siRNA-1/2 were detected using the LC/ESI-MS method. The results are presented as the percentage of the value of PA molecular species in glucose-unstimulated cells transfected with control siRNA or DGKδ-siRNA-1/2. DGKδ-siRNA-1/2 did not significantly affect the value of PA molecular species in glucose-unstimulated cells. The values are presented as the mean ± S.D. ($n = 4$). *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.005$ (no stimulation *versus* glucose stimulation). #, $p < 0.05$; ##, $p < 0.01$ (control siRNA *versus* DGKδ-siRNA-1 or DGKδ-siRNA-2).

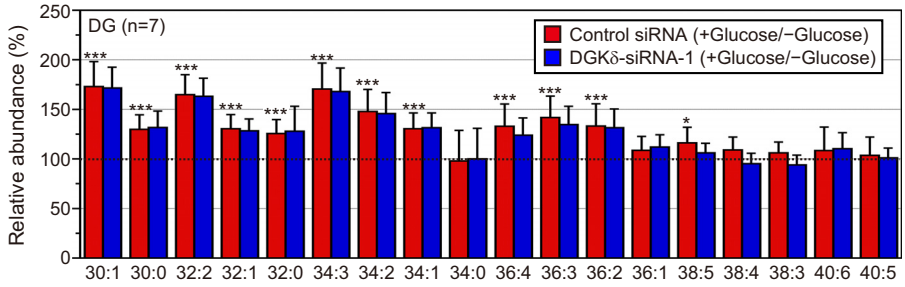

FIGURE 3. **Effect of DGKδ-siRNA-1 on high glucose-induced increases of DG molecular species in C2C12 myoblasts.** The major DG molecular species in the glucose-unstimulated or glucose-stimulated cells transfected with control siRNA or DGKδ-siRNA-1 were detected using the ESI-MS method. The results are presented as the percentage of the value of DG molecular species in glucose-unstimulated cells transfected with control siRNA or DGKδ-siRNA-1. DGKδ-siRNA-1 did not significantly affect the value of DG molecular species in glucose-unstimulated cells. The values are presented as the mean ± S.D. ($n = 7$). *, $p < 0.05$; ***, $p < 0.005$ (no stimulation *versus* glucose stimulation).

analysis revealed that the main fatty acid residues were as follows: 30:0 consisted of 14:0 and 16:0 (100%), 32:0 included 16:0 and 16:0 (96.6%), and 34:0 contained 16:0 and 18:0 (99.7%) (Table 1). These results indicate that 30:0-, 32:0-, and 34:0-PA consist of relatively short saturated fatty acids and commonly contain palmitic acid (16:0). It is possible that DGKδ2 also produces 30:1-, 32:1-, and 34:1-PA species (Figs. 2 and 4). These PA species contain saturated fatty acids, 16:0 and 14:0, and monounsaturated fatty acids, 16:1 and 18:1 (Table 1).

In Vitro DGKδ Activity—We examined whether the preference of DGKδ2 for palmitic acid (16:0)-containing DG species, 30:0-, 32:0-, and 34:0-DG, is an intrinsic catalytic feature of DGKδ. To this end, we measured DGKδ2 activity *in vitro* using 32:0 (16:0/16:0)-, 34:1 (16:0/18:1)-, or 38:4 (18:0/20:4)-DG as

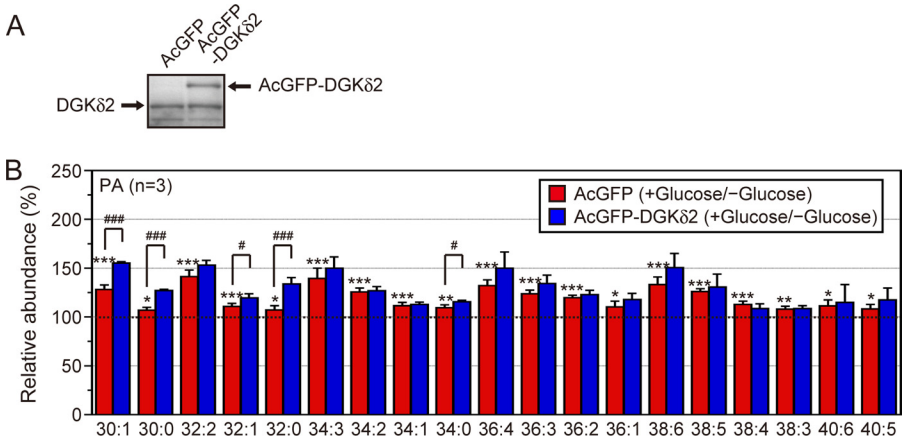

FIGURE 4. **PA molecular species in C2C12 cells stably expressing DGKδ2.** *A*, the stable expression of AcGFP-DGKδ2 in C2C12 cells was confirmed by Western blot analysis using the anti-DGKδ antibody. *B*, the major PA molecular species in the glucose-unstimulated or glucose-stimulated cells stably expressing human DGKδ2 were identified and quantified using LC/ESI-MS. The results are presented as the percentage of the value of PA molecular species in glucose-unstimulated cells transfected with AcGFP alone or AcGFP-DGKδ2. Overexpression of DGKδ2 did not significantly affect the value of PA molecular species in glucose-unstimulated cells. The values are presented as the mean ± S.D. ($n = 3$). *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.005$ (no stimulation *versus* glucose stimulation). #, $p < 0.05$; ###, $p < 0.005$ (no overexpression *versus* DGKδ overexpression).

TABLE 1
Identification of the acyl species in each PA molecular species

PA molecular species	Identified acyl chains[a]			
	%			
30:1	14:0/16:1 (86.0%)	16:0/14:1 (14.0%)		
30:0	14:0/16:0 (100%)			
32:2	16:1/16:1 (98.5%)	14:0/18:2 (1.5%)		
32:1	16:0/16:1 (88.7%)	14:0/18:1 (11.3%)		
32:0	16:0/16:0 (96.6%)	14:0/18:0 (3.4%)		
34:3	16:1/18:2 (67.2%)	16:2/18:1 (27.7%)	16:0/18:3 (5.1%)	
34:2	16:1/18:1 (86.3%)	16:0/18:2 (13.6%)	16:2/18:0 (0.1%)	
34:1	16:0/18:1 (93.2%)	18:0/16:1 (6.8%)		
34:0	16:0/18:0 (99.7%)	14:0/20:0 (0.3%)		
36:4	16:0/20:4 (83.0%)	16:1/20:3 (8.7%)	18:1/18:3 (7.2%)	18:2/18:2 (1.2%)
36:3	18:1/18:2 (74.9%)	16:0/20:3 (23.6%)	16:1/20:2 (0.8%)	18:0/18:3 (0.7%)
36:2	18:1/18:1 (91.6%)	18:0/18:2 (5.0%)	16:0/20:2 (2.5%)	16:1/20:1 (0.9%)
36:1	18:0/18:1 (87.8%)	16:0/20:1 (6.5%)	16:1/20:0 (5.6%)	14:0/22:1 (0.1%)
38:6	16:0/22:6 (68.0%)	16:1/22:5 (30.9%)	18:1/20:5 (1.1%)	
38:5	16:0/22:5 (45.0%)	18:1/20:4 (45.0%)	18:0/20:5 (8.5%)	16:1/22:4 (1.6%)
38:4	18:0/20:4 (80.1%)	18:1/20:3 (19.5%)	16:0/22:4 (0.4%)	
38:3	18:0/20:3 (88.6%)	18:1/20:2 (10.5%)	16:0/22:3 (0.9%)	
40:6	18:1/22:5 (51.5%)	18:0/22:6 (47.6%)	16:0/24:6 (0.9%)	
40:5	18:0/22:5 (97.4%)	18:1/22:4 (2.6%)		

[a] The relative abundance (%) was based on the peak areas of the fragment ions (ESI-MS/MS) for each molecular ion.

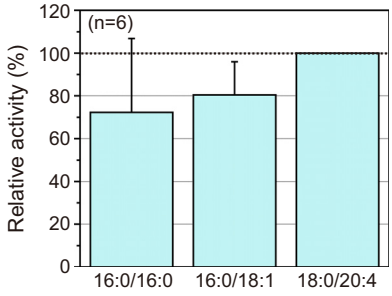

FIGURE 5. ***In vitro* DGKδ activity.** For measurement of *in vitro* DGKδ activity, 2 mM (5.4 mol%) 16:0/16:0-, 16:0/18:1-, and 18:0/20:4-DG were used as substrates. The activity of 3×FLAG-tagged DGKδ2 in COS-7 cells was compared with the control. The results are presented as the percentage of the value of activity against 18:0/20:4-DG. The values are presented as the mean ± S.D. ($n = 6$).

substrates. As shown in Fig. 5, the levels of 32:0- and 34:1-PA generated by DGKδ2 were similar to or slightly lower than that of 38:4-PA. These results indicate that DGKδ2 does not exhibit intrinsic substrate selectivity for particular DG molecular species, 32:0-DG, *in vitro*. Therefore, we hypothesized that DGKδ accomplishes apparent substrate selectivity in C2C12 cells by accessing a DG pool containing only 30:0-, 32:0-, and 34:0-DG, and not based on the intrinsic properties of the enzyme.

Effects of Inhibitors of Lipid Metabolism Enzymes on High Glucose Level-induced PA Production—To test this hypothesis, we next searched for the lipid metabolic pathway that supplies 30:0-, 32:0-, and 34:0-DG species as a substrate for DGKδ2. There are three pathways that produce DG, 1) the *de novo* pathway (30, 31), 2) the PLD/PA phosphatase pathway (32), and 3) the PC-specific PLC pathway (33). The treatment with 20 μM TOFA, which inhibits acetyl-CoA carboxylase involved in the *de novo* synthesis of DG (23, 24), did not decrease the glucose-stimulated production of PA molecular species (Fig. 6*A*). Moreover, 100 nM FIPI, which inhibits PLD involved in DG generation from PC through the action of PA phosphatase (25), reduced the amounts of most of the PAs in the absence of high glucose stimulation (data not shown). However, this compound failed to attenuate the glucose-stimulated production of PA molecular species (Fig. 6*B*). These results strongly suggest that these pathways are not involved in the DG supply to DGKδ2.

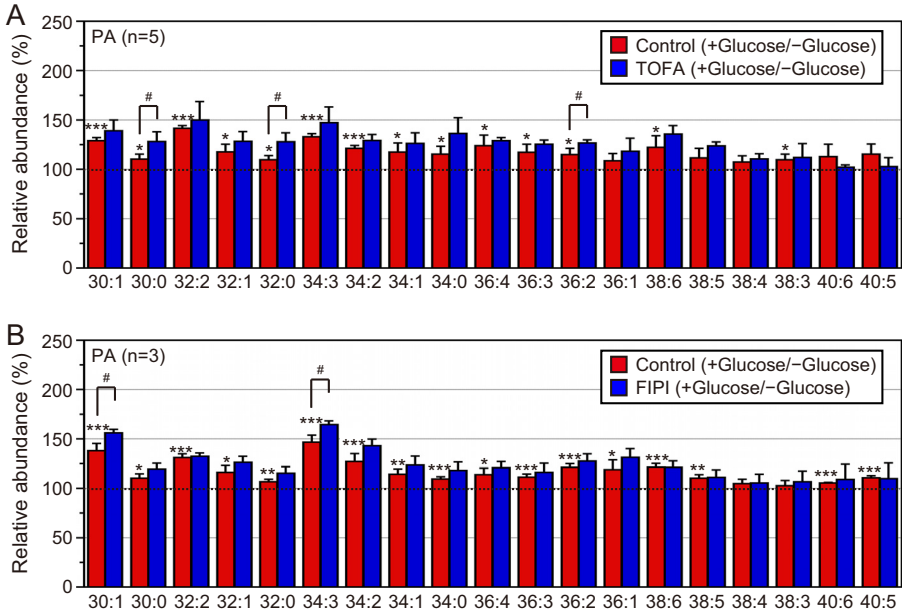

FIGURE 6. **Effects of TOFA and FIPI on the production of PA molecular species in glucose-stimulated C2C12 cells.** *A*, the major PA molecular species in glucose-unstimulated or glucose-stimulated cells treated with DMSO (control) or TOFA were detected using the LC/ESI-MS method. The results are presented as the percentage of the value of PA species in glucose-unstimulated cells treated with DMSO (control) or TOFA. The values are presented as the mean ± S.D. ($n = 5$). *, $p < 0.05$; ***, $p < 0.005$ (no stimulation *versus* glucose stimulation). #, $p < 0.05$ (without TOFA *versus* with TOFA). *B*, the major PA molecular species in the glucose-unstimulated or glucose-stimulated cells treated with DMSO (control) or FIPI were detected using the LC/ESI-MS method. The results are presented as the percentage of the value of PA species in glucose-unstimulated cells treated with DMSO (control) or FIPI. The values are presented as the mean ± S.D. ($n = 3$). *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.005$ (no stimulation *versus* glucose stimulation). #, $p < 0.05$ (without FIPI *versus* with FIPI).

D609 is an inhibitor of PC-PLC (22), which generates DG via PC hydrolysis (34). Treatment with 100 μM D609 strongly inhibited the high glucose stimulation-responsive production of 30:0-, 32:0-, and 34:0-PA to their basal levels (Fig. 7*A*), suggesting that DGKδ2 utilizes DG species supplied from the PC-PLC pathway.

We next confirmed that D609 inhibited the production of DG molecular species, including 30:0-, 32:0-, and 34:0-DG. This inhibitor statistically attenuated the amounts of 30:0-, 32:0-, and 34:0-DG in the absence of high glucose stimulation (Fig. 7*B*). However, D609 inhibited high glucose-dependent increases for all of the C30-C34 DG species (Fig. 7*C*). These results suggest that, in response to acute high glucose stimulation (5 min), DGKδ2 can utilize DG species that are supplied from the PC-PLC pathway, in both high glucose-independent and high glucose-dependent manners.

*Linkage between PC-PLC and DGK*δ—To further examine the linkage between the PC-PLC pathway and DGKδ2, we determined whether D609 and DGKδ-siRNA-1 additively affected the high glucose-dependent increases of 30:0-, 32:0-, and 34:0-PA. If DGKδ2 utilizes DG species supplied from the PC-PLC pathway, it would be expected that reduced expression of DGKδ2 via DGKδ-siRNA-1 would not enhance the effect of the PC-PLC inhibitor. It was confirmed that the expression of DGKδ2 was substantially reduced by DGKδ-siRNA-1, even in the presence of D609 (Fig. 8*A*). As shown in Fig. 8*B*, DGKδ-siRNA-1 failed to further inhibit the glucose-dependent increases of 30:0-, 32:0-, and 34:0-PA in the presence of D609. These results strongly suggest that 30:0-, 32:0-, and 34:0-DG phosphorylated by DGKδ2 in response to acute high glucose exposure are generated, at least in part, by PC hydrolysis catalyzed by PC-PLC.

We next examined whether DGKδ directly or indirectly interacted with PC-PLC. To this end, we used C2C12 cells stably overexpressing DGKδ2 (Fig. 4) and stimulated the cells with high glucose. We confirmed that DGKδ2 was immunoprecipitated with the anti-DGKδ antibody (Fig. 8*C*). Because the molecular identity of mammalian PC-PLC remains unclear (35), its antibody is unavailable. Therefore, we determined PC-PLC activity in the immunoprecipitates using the Amplex Red® PC-PLC assay kit, which detects phosphocholine generated by PC-PLC. As demonstrated in Fig. 8*D*, PC-PLC activity was clearly co-immunoprecipitated with DGKδ2. The assay does not detect the activity of sphingomyelin synthase, which produces DG and sphingomyelin, but not phosphocholine. The contribution of PLD, which hydrolyzes PC to PA and choline, can be accounted for by elimination of alkaline phosphatase from the assay (see "Experimental Procedures"). However, when the assay was performed in the absence of alkaline phosphatase, the activity was not detectable. Taken together, these results strongly suggest that DGKδ2 utilizes DG species supplied from PC-PLC-dependent PC hydrolysis in response to high glucose (Fig. 9).

DISCUSSION

The increase in PA molecular species by stimulation with high glucose levels has not been identified until now. Moreover, it has not been reported that high glucose induces total PA production. The main reasons for this are that PA species are minor components and it is difficult to quantify the amounts of PA molecular species using conventional LC/ESI-MS methods. To overcome this difficulty, we recently established an LC/ESI-MS method specialized for PA species (21). In this study, we revealed for the first time that acute high glucose

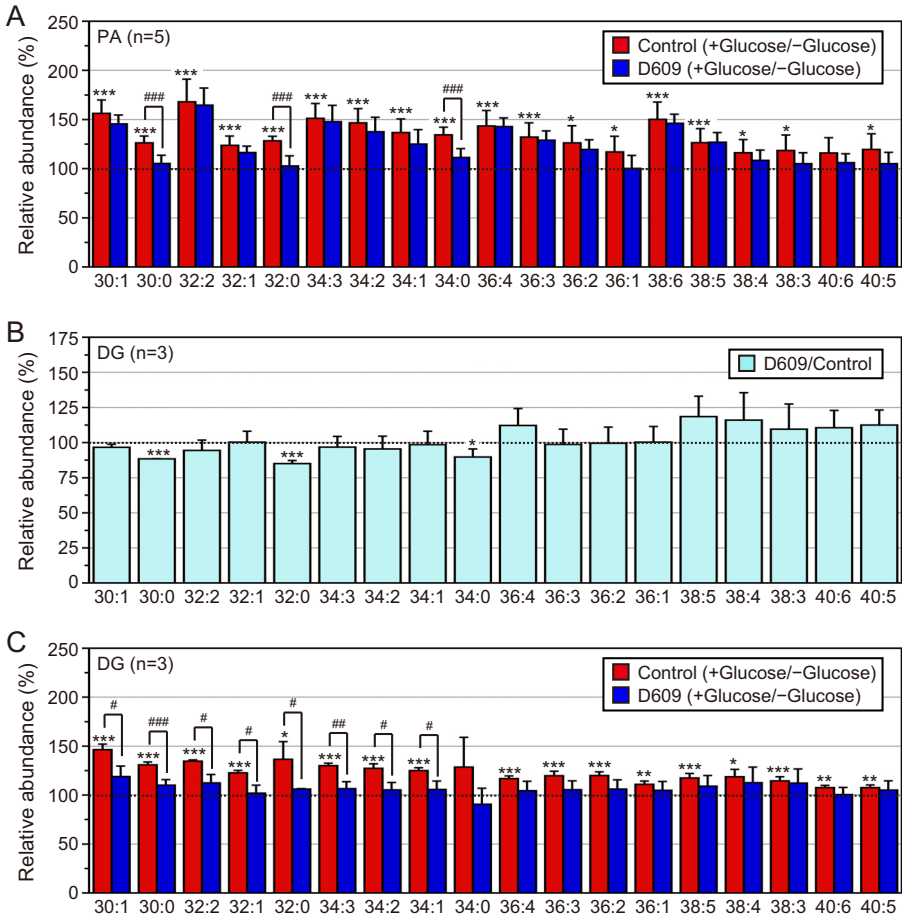

FIGURE 7. **Effect of D609 on high glucose-induced increases in PA and DG molecular species in C2C12 myoblasts.** *A*, the major PA molecular species in the glucose-unstimulated or glucose-stimulated cells treated with DMSO (control) or D609 were detected using the LC/ESI-MS method. The results are presented as the percentage of the value of PA molecular species in glucose-unstimulated cells treated with DMSO (control) or D609. D609 did not significantly affect the value of PA molecular species in glucose-unstimulated cells. The values are presented as the mean ± S.D. ($n = 5$). *, $p < 0.05$; ***, $p < 0.005$ (no stimulation *versus* glucose stimulation). ###, $p < 0.005$ (without D609 *versus* with D609). *B* and *C*, the major DG molecular species in the glucose-unstimulated or glucose-stimulated cells treated with DMSO (control) or D609 were detected using the ESI-MS method. *B*, comparison of +D609 *versus* −D609 in the absence of glucose. The results are presented as the percentage of the value of DG species in glucose-unstimulated cells treated with DMSO (control). The values are presented as the mean ± S.D. ($n = 3$). *, $p < 0.05$; ***, $p < 0.005$. *C*, comparison of +glucose *versus* −glucose in the absence or presence of D609. The results are presented as the percentage of the value of DG species in glucose-unstimulated cells treated with DMSO (control) or D609. D609 did not significantly affect the value of DG molecular species in glucose-unstimulated cells. The values are presented as the mean ± S.D. ($n = 3$). *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.005$ (no stimulation *versus* glucose stimulation). #, $p < 0.05$; ##, $p < 0.01$; ###, $p < 0.005$ (without D609 *versus* with D609).

stimulation statistically increased the PA mass and number of molecular species using the newly developed method (Fig. 1). The results indicate that our LC/ESI-MS method is a powerful tool for detecting even small changes in PA molecular species.

The suppression of DGKδ expression by RNA silencing decreased the high glucose-induced production of 30:0-, 32:0-, 34:1-, and 34:0-PA in C2C12 myoblasts (Fig. 2). Moreover, the levels of 30:1-, 30:0-, 32:1-, 32:0-, and 34:0-PA were substantially increased in a high glucose-dependent manner in C2C12 cells stably expressing DGKδ2 when compared with control cells (Fig. 4). Taken together, these results strongly suggest that DGKδ preferentially generates 30:0-, 32:0-, and 34:0-PA, which contain two saturated fatty acids, in the cells. The main fatty acid residues of these PA species were 14:0 and 16:0, 16:0 and 16:0, and 16:0 and 18:0, respectively (Table 1). These results suggest that DGKδ produces PA with an apparent preference for palmitic acid (16:0)-containing PA. Moreover, the suppression of DGKδ expression by siRNA-1 and -2 also decreased the high glucose-induced production of 34:1-PA (Fig. 2). The overexpression of DGKδ2 statistically increased the levels of 30:1- and 32:1-PA (Fig. 4). The DGKδ suppression also modestly attenuated 30:1- and 32:1-PA levels (Fig. 2), and the DGKδ2 overexpression slightly augmented 34:1-PA production (Fig. 4). Therefore, it is possible that this enzyme also generates 30:1-, 32:1-, and 34:1-PA, which contain one saturated and one monounsaturated fatty acid, in addition to 30:0-, 32:0-, and 34:0-PA. 30:1-, 32:1-, and 34:1-PA contain saturated fatty acids, 16:0 and 14:0, and monounsaturated fatty acids, 16:1 and 18:1 (Table 1). The DGKδ-siRNAs and DGKδ overexpression failed to statistically affect the amounts of high glucose-induced increases of 32:2-, 34:3-, 34:2-, 36:4-, 36:3-, 36:2-, and 38:6-PA (Figs. 2 and 4), implying that these PA species were generated by other DGK isozyme(s).

DGK is a member of the PI turnover pathway and initiates resynthesis of PI (18). This fact led us to believe that DGK isozymes, including DGKδ, also exhibit selectivity against 38:4 (18:0/20:4)-DG derived from PI turnover. Indeed, it was reported that DGKϵ preferentially phosphorylated DGs con-

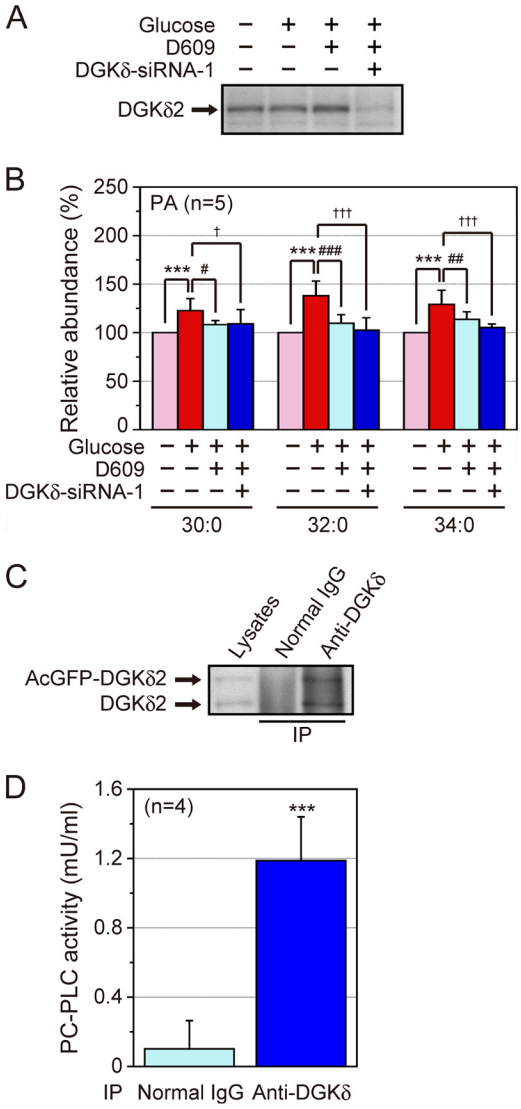

FIGURE 8. **Examination of the functional linkage between PC-PLC and DGKδ.** Effects of D609 and DGKδ-siRNA-1 on high glucose-induced increases of PA molecular species in C2C12 myoblasts were compared. *A*, the suppression of DGKδ2 expression by DGKδ-siRNA-1 was confirmed by Western blot analysis using the anti-DGKδ antibody. *B*, 30:0-, 32:0-, and 34:0-PA in the glucose-unstimulated or glucose-stimulated cells treated with DMSO (control), D609, or D609 and DGKδ-siRNA-1 were detected using the LC/ESI-MS method. The results are presented as the percentage of the value of PA molecular species in glucose-unstimulated cells. The values are presented as the mean ± S.D. ($n = 5$). ***, $p < 0.005$ (no stimulation *versus* glucose stimulation). #, $p < 0.05$; ##, $p < 0.01$; ###, $p < 0.005$ (without D609 *versus* with D609). †, $p < 0.05$; †††, $p < 0.005$ (control siRNA *versus* DGKδ-siRNA-1). *C* and *D*, co-immunoprecipitation of PC-PLC activity with DGKδ2. *C*, immunoprecipitation (*IP*) of DGKδ2 using the anti-DGKδ antibody was confirmed by Western blot analysis using the anti-DGKδ antibody. *D*, PC-PLC activity in the precipitates was measured using the Amplex Red® PC-PLC assay kit. The values are presented as the mean ± S.D. ($n = 4$). ***, $p < 0.005$. When the assay was performed in the absence of alkaline phosphatase, the activity was not detectable.

taining arachidonic acid (*e.g.* 38:4 (18:0/20:4)-DG) derived from PI turnover (7, 19, 20). However, high glucose stimulation did not increase the amount of 38:4-PA (Figs. 1 and 2), which mainly consisted of 18:0/20:4-PA (Table 1). Moreover, DGKδ-siRNAs and DGKδ2 overexpression failed to affect the amounts of 38:4-PA in response to high glucose stimulation (Figs. 2 and 4). These results indicate that DGKδ does not phosphorylate 38:4-DG derived from PI turnover in a glucose-dependent manner.

DGKδ did not exhibit selectivity against 16:0/16:0 (32:0)- or 16:0/18:1 (34:1)-DG *in vitro* (Fig. 5). Therefore, we hypothesized that DGKδ exerts substrate selectivity in C2C12 cells through accessing a DG pool containing 30:0-, 32:0-, and 34:0-DG, and not via its intrinsic preference. There are three DG supply pathways, *i.e.* 1) *de novo* synthesis including acetyl-CoA carboxylase (30, 31), 2) the PLD/PA phosphatase route (32), and 3) PC hydrolysis by PC-specific PLC (33). Treatment with the PC-PLC inhibitor D609, but not inhibitors of acetyl-CoA carboxylase and PLD, strongly inhibited the high glucose stimulation-responsive production of 30:0-, 32:0-, and 34:0-PA (Fig. 7*A*). Moreover, RNA silencing of DGKδ failed to further inhibit the glucose-dependent increases in 30:0-, 32:0-, and 34:0-PA in the presence of D609 (Fig. 8*B*). Furthermore, PC-PLC was co-immunoprecipitated with DGKδ2 (Fig. 8*D*). Taken together, these results strongly suggest that 30:0-, 32:0-, and 34:0-DG phosphorylated by DGKδ2 in response to acute high glucose exposure are generated, at least in part, by PC hydrolysis catalyzed by PC-PLC (Fig. 9).

The role of sphingomyelin synthase as a potential PC-PLC was indicated (36). We cannot rule out the possibility that DGKδ2 partly utilizes sphingomyelin synthase-dependent DG. However, it is likely that DGKδ2 phosphorylates DG species generated, at least in part, by PC-PLC because the co-immunoprecipitates with DGKδ2 contained PC-PLC activity.

The molecular identity of PC-PLC remains unclear (35). In this study, DGKδ was revealed to directly or indirectly associate with PC-PLC. With the pulldown of PC-PLC activity with DGKδ2, there may be an opportunity to identify the unidentified PC-PLC enzyme by proteomics approaches. Therefore, DGKδ2 may serve as a good tool to search for the PC-PLC molecule.

D609 attenuated high glucose-dependent increases in various C30-C34 DG species (Fig. 7*C*). However, D609 strongly inhibited only the high glucose stimulation-responsive production of 30:0-, 32:0-, and 34:0-PA (Fig. 7*A*). Intriguingly, this inhibitor statistically reduced the amounts of 30:0-, 32:0-, and 34:0-DG in the absence of high glucose (Fig. 7*B*). Therefore, it is likely that, in response to acute high glucose stimulation (5 min), DGKδ2 mainly utilizes these DG species supplied from the PC-PLC pathway in a high glucose-independent manner. Moreover, DGKδ2 can generate 30:1-, 32:1-, and 34:1-PA, in addition to 30:0-, 32:0-, and 34:0-PA. (Figs. 2 and 4). Although D609 moderately attenuated 30:1-, 32:1-, and 34:1-PA generation (Fig. 7*A*), this inhibitor did not affect the amounts of 30:1-, 32:1-, and 34:1-DG in the absence of high glucose stimulation (Fig. 7*B*). However, D609 substantially inhibited high glucose-dependent increases for 30:1-, 32:1-, and 34:1-DG (Fig. 7*C*). These results suggest that DGKδ2 can utilize 30:1-, 32:1-, and 34:1-DG that are supplied from the PC-PLC pathway in a high glucose-dependent manner.

Recently, Shulga *et al.* (37) and Lowe *et al.* (38) reported that DGKδ positively regulated lipid synthesis, including DG and PA, during adipocyte differentiation. However, unlike for acute high glucose stimulation, a significant preference against DG and PA was not found. The increases were, at least in part, a

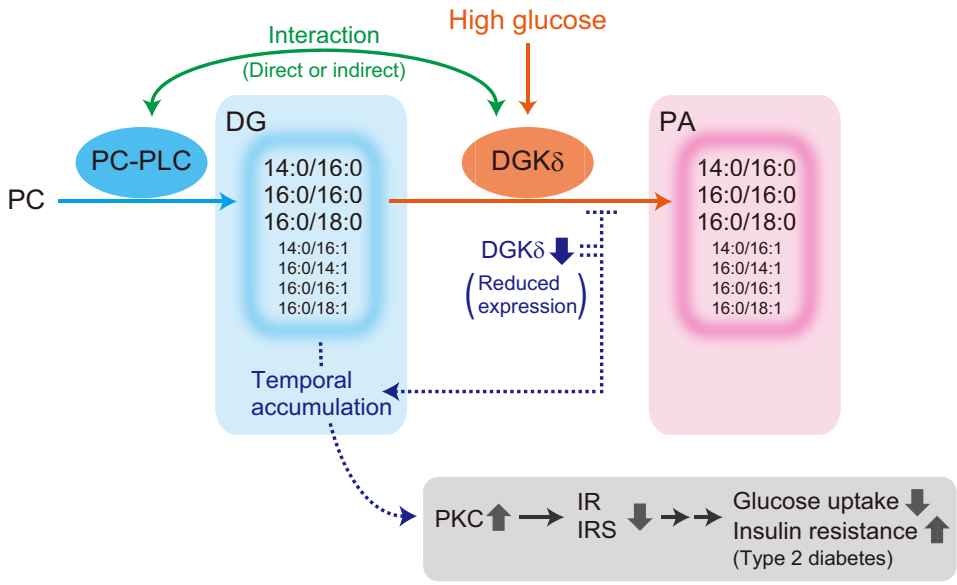

FIGURE 9. **Model for the metabolism pathway utilized by DGKδ.** *IR*, insulin receptor; *IRS*, insulin receptor substrate.

result of promoting the *de novo* synthesis of fatty acids. However, in this study, an inhibitor of acetyl-CoA carboxylase TOFA did not decrease glucose-stimulated PA production (Fig. 6*A*). Because differentiation is a long term event, the difference between acute high glucose stimulation in C2C12 myoblasts and adipocyte differentiation may be due to distinct supply pathways and/or fatty acid conversion during long term culture through the remodeling pathway (Lands' cycle) (39).

Chibalin *et al.* (15) previously reported that the transcription of DGKδ and the levels of DGKδ protein were also reduced in skeletal muscle from type II diabetes patients. Moreover, in DGKδ haploinsufficient mice (DGKδ$^{+/-}$), the accumulation of DG, which was caused by decreases in total DGK activity and DGKδ protein levels in skeletal muscle, increased phosphorylation of PKCδ and suppressed protein expression of the insulin receptor and insulin receptor substrate-1 for insulin signaling, resulting in the aggravation of type II diabetes (15). Another study reported that the accumulation of DG molecular species with palmitic acid (16:0) is involved in insulin resistance (40). It is generally accepted that saturated fatty acids including palmitic acid induce insulin resistance (41–43). In this study, MS/MS analysis demonstrated that 30:0-, 30:1-, 32:0-, 32:1-, 34:0-, and 34:1-PA commonly contained palmitic acid (16:0), and suggests that DGKδ mainly consumes 30:0-, 30:1-, 32:0-, 32:1-, 34:0-, and 34:1-DG containing palmitic acid (16:0) supplied from the PC-PLC pathway for glucose uptake in skeletal muscle in a glucose-dependent manner. Acute high glucose- and DGKδ-dependent increases in 30:0-, 30:1-, 32:0-, 32:1-, 34:0-, and 34:1-PA were relatively minor changes (20–30% increases) when compared with the total amounts of each PA species (Figs. 1 and 2). DGKδ, which was temporarily activated within 5 min (16), showed a distinct punctate localization pattern in C2C12 cells (17). Therefore, a possible explanation of these findings is that these DGKδ-dependent minor changes of DG/PA species in temporally and spatially restricted regions play a role in modulating insulin signaling. However, further studies are required to elucidate the relationship between the specific DG species accumulation in type II diabetes patients and the PC-PLC-DGKδ pathway disclosed here.

In summary, the present study strongly suggests that DGKδ preferentially consumes palmitic acid (16:0)-containing DG species such as 30:0-, 30:1-, 32:0-, 32:1-, 34:0-, and 34:1-DG, but not arachidonic acid (20:4)-containing DG species derived from the phosphatidylinositol turnover, in glucose-stimulated C2C12 myoblasts (Fig. 9). Moreover, an unexpected linkage between PC-PLC and DGKδ emerged. The route "PC → PC-PLC → DG → DGK → PA" proposed here (Fig. 9) is a novel DG metabolic pathway. This new pathway is proposed to play an important role in glucose uptake in skeletal muscle and to be involved in the pathogenesis of type 2 diabetes.

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