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Substrate Chirality and Specificity of Diacylglycerol Kinases and the Multisubstrate Lipid Kinase[†]

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ABSTRACT: The α , ζ , and ϵ isoforms of diacylglycerol kinase exhibit a high degree of stereospecificity in the phosphorylation of diacylglycerol. In comparison, a multiple lipid kinase, MuLK, shows much less stereospecificity, phosphorylating 1,2-dioleoylglycerol only ~ 2 – 3 times more rapidly than 2,3-dioleoylglycerol. The α and ζ isoforms of diacylglycerol kinase are inhibited by 2,3-dioleoylglycerol, but not the more substrate-selective ϵ isoform. The inhibition by 2,3-dioleoylglycerol is uncompetitive. This corresponds to a kinetic scheme in which the inhibitor can bind to the enzyme–substrate complex, but not to the free enzyme. Our data indicate that despite their similar structures, 1,2-dioleoylglycerol and 2,3-dioleoylglycerol do not compete for the active site of these three isoforms of diacylglycerol kinase. We suggest that the 2,3-dioleoylglycerol binds to a site on the α and ζ isoforms of diacylglycerol kinase that is exposed as a consequence of the substrate binding to the active site. The chiral specificity of these enzymes thus mimics the substrate specificity, with MuLK being the least selective and the ϵ isoform of diacylglycerol kinase exhibiting the greatest selectivity.

Mammalian diacylglycerol kinases (DGKs)¹ make up a family of enzymes that catalyze the production of phosphatidic acid from diacylglycerol (DAG) and ATP. These enzymes are believed to have important roles in DAG signaling (1, 2). Another lipid kinase that phosphorylates diacylglycerol is the multisubstrate lipid kinase (MuLK) (3, 4). This enzyme resembles bacterial DGK in having less specificity for the lipid substrate it phosphorylates (3), although its sequence is more homologous to those of mammalian forms of DGK, and it is not an integral membrane protein like the bacterial DGKs (5). The sequence of MuLK also is significantly similar to those of sphingosine kinases. Because it catalyzes the phosphorylation of DAG at a higher rate than other lipids (3), it can be considered as a form of DGK.

There are only two widely utilized inhibitors of mammalian DGKs. These are 6-(2-{4-[(4-fluorophenyl)phenylmethylene]-1-piperidinyl}ethyl)-7-methyl-5H-thiazolo[3,2- α]pyrimidin-5-one, termed R59022 (6), and 3-(2-{4-[bis(4-fluorophenyl)methylene]-1-piperidinyl}ethyl)-2,3-dihydro-2-thioxo-4(1H)-quinazolinone, known as R59949 (7). R59949 appears to bind to the catalytic domain of the enzyme (8). Neither of these inhibitors is very specific for a particular isoform of DGK, although R59949 exhibited somewhat greater inhibition with calcium-dependent isoforms of this enzyme (8). With DGK isoforms from *Arabidopsis thaliana*, R59022 exhibits greater inhibition with AtDGK2 than with another isoform from this organism, AtDGK7 (9). These two inhibitors have been used extensively in pharmacological studies of the role of DGK in mammalian cells (see, for example, refs 10–14).

One would anticipate that lipids having a close structural relationship with the natural substrates, 1,2-DAGs, would be either inhibitors or themselves substrates of DGK. The structurally related 1,3-DAGs are not substrates for DGK ζ (15). Ceramide, a lipid with a single hydroxyl group like DAG, was found to be a competitive inhibitor of a Ca²⁺-dependent isoform of DGK (16). It has also been shown recently that a homologue of the mammalian diacylglycerol kinases, YegS, has specificity for an unrelated lipid, phosphatidylglycerol (17).

Enantiomers (mirror-image forms) of substrates are often found to be inhibitors of enzymes. In the case of the substrate

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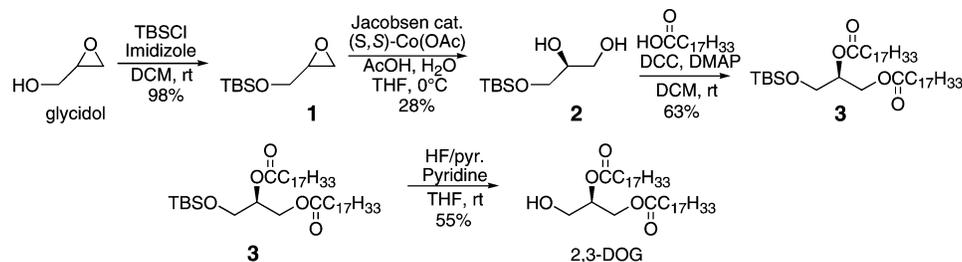
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¹ Abbreviations: DGK, diacylglycerol kinase; MuLK, multisubstrate lipid kinase; 2,3-DOG, 2,3-dioleoylglycerol; 1,2-DOG, 1,2-dioleoylglycerol; SAG, 1-stearoyl-2-arachidonoylglycerol; PA, phosphatidic acid; MOI, multiplicity of infection; CL, cardiolipin; DAG, diacylglycerol; DCC, *N,N'*-dicyclohexylcarbodiimide; DMAP, dimethylaminopyridine; DCM, dichloromethane.

Scheme 1: Revised Synthesis of 2,3-DOG



1,2-diacylglycerol, there is one chiral center at the C-2 position of glycerol. The enantiomer of 1,2-diacylglycerol is 2,3-diacylglycerol. We determined the chiral specificity of several forms of DGK as well as the action of 2,3-diacylglycerol as an inhibitor of MuLK and different isoforms of mammalian DGK.

EXPERIMENTAL PROCEDURES

Materials

Lipids, except for 2,3-dioleoylglycerol (2,3-DOG), were purchased from Avanti Polar Lipids (Alabaster, AL). Histone HI was from GIBCO/BRL (Grand Island, NY); ATP was the disodium salt, SigmaUltra grade (Sigma, St. Louis, MO). [γ - 32 P]ATP was from Perkin-Elmer (Boston, MA). Other chemicals were of the purest available grade. Double-distilled water was used for all solutions.

Synthesis of 2,3-DOG

An initial synthesis of 2,3-DOG was adapted from a general synthesis of diacylglycerols (18). This route provided initial samples for enzyme analysis; however, the purity of the products was not optimal, and a second, improved synthesis of 2,3-DOG was developed. The second route began with racemic glycidol. Glycidol was distilled and then reacted with *tert*-butyldimethylsilyl chloride (TBSCl) to form the TBS-protected glycidol **1** (Scheme 1). Epoxide **1** was then reacted with the Jacobsen's chiral (*S,S*)-salen cobalt catalyst under hydrolytic kinetic resolution conditions to yield diol **2** (19). This species was then acylated with oleic acid, using *N,N*-dicyclohexylcarbodiimide (DCC) and dimethylaminopyridine (DMAP), to yield 2,3-diacyl TBS ether **3**. After multiple deprotection methods had been screened, HF-pyridine conditions were found to be the most dependable. TBS ether **3** was reacted with HF-pyridine in excess pyridine to yield 2,3-DOG.

TBS-Protected Glycidol (1). Glycidol was distilled via short path distillation (62 °C at 15 Torr). A mixture of 10 mL (0.15 mol) of glycidol, 22.61 g (0.150 mol) of TBSCl, and 12.25 g (0.18 mol) of imidazole in 500 mL of dichloromethane (DCM) was stirred at 0 °C for 1.5 h. The mixture was washed with NH_4Cl and brine and extracted with DCM, dried over sodium sulfate (overnight), filtered, and concentrated to yield 27.9 g (98%) of TBS-protected glycidol **1**: $^1\text{H NMR}$ (500 MHz, CDCl_3) δ 0.10 (6 H, t, TBS methyls), 0.90 (9 H, m, TBS tBu); glycidol backbone protons δ 2.60 (1 H, dd), 2.75 (1 H, dd), 3.10 (1 H, m, methine), 3.70 (1 H, dd), 3.85 (1 H, dd).

2,3-Diol TBS Ether (2). A sample of 160.4 mg (2.65 mmol) of Jacobsen (*S,S*)-Co(salen)(OAc) catalyst was dissolved in 4 mL of toluene, to which 60 μL (1.06 mmol)

of AcOH was added (19). This mixture was stirred open to air, and toluene was then removed under reduced pressure. A sample of 10 g (53.1 mmol) of epoxide **1** was added to this activated catalyst species along with 1 mL of THF. The solution was cooled to 0 °C, and 430 μL of H_2O (23.9 mmol) was added dropwise. The mixture was stirred overnight. The diol product was separated from the mixture by fractional distillation to yield of 3.11 g (14.9 mmol, 28%): $^1\text{H NMR}$ (500 MHz, CDCl_3) δ 0.10 (6 H, t, TBS methyls), 0.90 (9 H, m, TBS tBu), 1.65 (1 H, s, OH), 2.60 (1 H, s, OH), 2.70 (6 H, m, carbon backbone and trace DCM).

2,3-Diacyl TBS Ether (3). A sample of 504 mg (2.44 mmol) of diol **2** was dissolved in 10 mL of dry DCM. To this solution were added 1.52 g (5.37 mmol) of oleic acid, 656 mg (5.37 mmol) of DMAP, and 2.27 g (11.0 mmol) of DCC. After being stirred for 48 h at 23 °C, the mixture was extracted with DCM, dried over sodium sulfate, filtered, and concentrated. Purification of this mixture was very difficult, and multiple chromatographies over silica gel were run with different solvent gradients (0 to 2% EtOAc/Hex). Following this process, 1.12 g (63%) of pure diacyl lipid **3** was isolated: $^1\text{H NMR}$ (500 MHz, CDCl_3) δ 0.10 (6 H, t, TBS methyls), 0.90 (9 H, m, TBS tBu), 3.70 (2 H, d, acylO- CH_2), 4.20 (1 H, dd, TBSO- CH_2), 4.35 (1 H, dd, TBSO- CH_2), 5.10 (1 H, m, methine), 5.35 (4 H, m, $\text{CH}=\text{CH}$).

2,3-DOG. A sample of 200 mg (27.2 mmol) of diacyl TBS ether **3** was added to a small Nalgene bottle along with 3 mL of THF and 0.5 mL of pyridine. A few drops of HF-pyridine was added, and the mixture was stirred overnight. The mixture was suspended in sodium bicarbonate and extracted with ether, dried over sodium sulfate, filtered, and concentrated. The mixture was purified on a small column (10% EtOAc/Hex) to yield 94 mg (15 mmol, 55%) of 2,3-DOG: $^1\text{H NMR}$ (500 MHz, CDCl_3) δ 0.90 (6 H, t, CH_3 -), 1.30 (~42 H, d, hydrocarbon), 1.50 (4 H, m, hydrocarbon), 2.05 (8 H, m, hydrocarbon), 2.35 (4 H, m, -O- CH_2 -), 3.75 (2 H, d, acylO- CH_2), 4.25 (1 H, dd, HO- CH_2), 4.35 (1 H, dd, HO- CH_2), 5.10 (1 H, m, methine), 5.35 (4 H, m, $\text{CH}=\text{CH}$).

While many enantiomeric purity analyses were explored, Mosher's ester derivatization proved to be the most useful. Precedent for this method from the related 2,3-DPG analysis had been developed (18). Many physical separation methods for determination of the ee (enantiomeric excess, i.e., the difference in amount between one enantiomer and the other) of the 2,3-DOG sample (chiral HPLC, chiral GC) failed to separate the enantiomers of the diacylglycerol. The Mosher's ester synthesis used a procedure involving the formation of Mosher's chloride in situ, followed by a direct treatment of the acyl chloride with the chiral alcohol under investigation (20).

Synthesis of Mosher's Acid Chloride. Approximately 10 mg of (*R*)-(+)- α -methoxy- α -trifluoromethylphenylacetic acid (MTPA) was treated with excess (>5 equiv) oxalyl chloride and a slight excess (>2 equiv) of DMF in 1 mL of hexanes. This mixture was stirred for 1 h. The precipitate of the reaction was then removed by filtration through a cotton plug, and the hexanes containing MTPACl were added to a flask containing the 2,3-DOG sample and pyridine.

Mosher's Ester Derivatization. A vial was prepared containing 4.9 mg (7.80 μ mol) of the 2,3-DOG sample and an excess of pyridine. The MTPACl/hexane solution was filtered into the vial, and a small crystal of DMAP was added. The mixture was allowed to stand overnight. Crude NMR analysis showed complete conversion of the 2,3-DOG sample to a Mosher's derivative. The presence of two doublets of doublets in the region of 4.2–4.4 ppm (and absence of two) indicated an enantiomeric ratio of greater than 95:5. A racemic standard was synthesized to compare with the 2,3-DOG spectra. The racemate showed the presence of four doublets of doublets in the region of 4.2–4.4 ppm, agreeing with the literature report (18), and supporting the enantiomeric analysis of the 2,3-DOG sample. It was concluded on the basis of the established data from the Jacobsen transformation and the observations of the Mosher's derivatization that 2,3-DOG was synthesized at an enantiomeric ratio of at least 95:5.

Preparation of DGK ζ and DGK ϵ

cDNAs encoding human DGK ζ with a C-terminal FLAG epitope tag or human DGK ϵ with a C-terminal six-His tag were cloned into BacPAK6 (Clontech), and baculovirus stocks were generated using the BacPAK system protocol (Clontech). Following the BacPAK system protocol, Sf21 cells were cultured and then infected with the virus stocks. Seventy-two hours later, cells were harvested in 50 mM HEPES (pH 7.4), 150 mM NaCl, 5 mM MgCl₂, 1% NP40, 1 mM DTT, 1 mM PMSF, 0.5 mM sodium orthovanadate, and leupeptin, pepstatin, aprotinin, and soybean trypsin inhibitor (10 μ g/mL each). The pellet was collected by centrifugation at 6000g for 5 min at 4 °C and stored at –80 °C until it was used. Expression of recombinant protein was verified by Western blot analysis using anti-DGK ζ , anti-DGK ϵ , or anti-His antibodies (Penta-his, Qiagen Inc., Mississauga, ON).

Preparation of DGK α

cDNA encoding human DGK α was cloned into pBlue-BacHis (Invitrogen), which attaches an N-terminal six-His tag. As described above, baculovirus stocks were prepared and used to infect Sf-9 insect cells, which were harvested 50 h post-infection in the buffer described for DGK ζ and ϵ . The Sf-9 cells were routinely maintained in SF 900 II serum free medium (Invitrogen Life Technologies, Carlsbad, CA) in Erlenmeyer flasks (Corning; 125–250 mL, working volume of 30–60 mL) agitated in an incubator shaker at 110 rpm and 27 °C. Production of recombinant protein was conducted in Erlenmeyer shaker flasks (1 L, working volume of 500 mL) by infecting cells growing exponentially at a density of 2.5–3 \times 10⁶ cells/mL with the baculovirus at a MOI of 10 plaque forming units per cell. The infection process was monitored by measuring the cell number and

the increase in average cell size. The culture was harvested 50 h post-infection, at a final viability of 90%. The culture supernatant was centrifuged at 500g (J6B, Beckman, Fullerton, CA) for 10 min at 4 °C. The cell pellets were collected and washed once with PBS and then stored –80 °C until they were used. The production of recombinant protein was verified by Western blot analysis using anti-His antibody (Penta-his, Qiagen Inc.).

Purification of Recombinant MuLK-FLAG from *Escherichia coli*

A protease deficient strain of *E. coli*, BL-21, was used for expression of this protein. MuLK-FLAG fusion protein was expressed in the pFLAG-CTC vector and purified with the FLAG affinity gel as follows. Briefly, after induction with 100 μ M IPTG for 4 h at 30 °C, cells expressing either a control fusion protein (Synaptic Vesicle Protein 2, amino truncation) or MuLK-FLAG were harvested, sonicated, and centrifuged for 20 min at 20000g. Lysates were incubated for 16 h with FLAG-affinity gel (Sigma) and subsequently washed in a batchwise manner three times with 10 mM MOPS (pH 7.2), 25 mM NaCl, and 1 mM EGTA (wash buffer), one time with 10 mM MOPS, 300 mM NaCl, and 1 mM EGTA, and one additional time with wash buffer. The FLAG-tagged protein was then eluted with 100 μ g/mL 3 \times FLAG peptide (Sigma) in 10 mM MOPS (pH 7.2), 50 mM NaCl, 1 mM EGTA, and protease inhibitors (Sigma). The eluted purified protein was stored in 20% (v/v) ethylene glycol (Fisher) at –20 °C. The protein concentration of the eluted purified protein was determined by a BCA protein assay.

Assay of the Enzymatic Activity of DGK α , ϵ , and ζ

The Triton micelle-based assay was based on published procedures (22–24). Briefly, a cell pellet from cells over-expressing either DGK α or DGK ζ was extracted with 2 M KCl in 33 mM Tris-HCl (pH 8.0) with 67 mM NaCl and 5 μ g/mL histone. The cells were spun in an ultracentrifuge for 30 min at 100000g and 20 °C. In the case of DGK ϵ , the enzyme was not efficiently extracted from the cell pellet with a salt solution but was solubilized by addition of 30 mM octyl glucoside to the KCl solution. The mixture was briefly vortexed and placed in a 30 °C water bath for 10 min.

A lipid film was made from a solution of lipid in CHCl₃ and CH₃OH (2:1) by evaporation of the solvent under a stream of N₂. The lipid was deposited on the walls of a glass culture test tube and then placed under vacuum for at least 2 h. The lipid film was solubilized in a Triton buffer, the enzyme preparation added, and the reaction mixture equilibrated for 5 min at 25 °C. The reaction was initiated by adding 20 μ L of 5 mM [γ -³²P]ATP (50 μ Ci/mL). The final assay mixture contained 15 mM Triton X-100, 50 mM Tris-HCl, 100 mM NaCl, 5 mM MgCl₂, 1 mM EGTA (pH 7.2), 1 mM DTT, and enzyme either with or without 2.5 mM Ca²⁺, as well as phospholipid and DAG as indicated. The reaction was carried out for 10 min at 25 °C and was terminated by the addition of 2 mL of a CHCl₃/CH₃OH mixture (1:1, v/v) containing 0.25 mg/L dihexadecyl phosphate. The organic phase was washed three times with 2 mL each of 1% HClO₄ and 0.1% H₃PO₄ in a H₂O/methanol mixture (7:1, v/v). The volume of the final organic phase was 0.80 mL. A 0.40 mL

Table 1: Chiral Specificities of DGK Isoforms

isoform	% activity ^a	conditions
DGK α	8.5 \pm 1	0.8 mM DOG, 5 mM DOPS
DGK ζ	12 \pm 2	0.8 mM DOG, 5 mM DOPS
DGK ϵ	6 \pm 1 ^b	1 mM DOG, 18 mM DOPC
MuLK	33 \pm 1	2.5 mM DOG, 1 mM CL

^a Rate of DGK-catalyzed phosphorylation of 2,3-DOG to 1,2-DOG expressed as a percentage. ^b The % activity of DGK ϵ against 2,3-DOG vs the preferred substrate for this isoform, i.e., 1-stearoyl-2-arachidonoyl glycerol, is 2.3 \pm 0.4.

aliquot of the organic phase was placed in a scintillation vial to assess the incorporation of ³²P into phosphatidic acid by Cerenkov counting. Without the addition of exogenous lipid substrate, there was no incorporation of ³²P from ATP into endogenous lipids. Blanks were run without the addition of enzyme or with enzyme preparations from mock transfected cells. The assay was carried out in triplicate, and the results are presented with errors showing the standard deviation of the mean for one experiment.

Assay of Enzymatic Activity of MuLK

A dried lipid film was prepared as described above containing a DAG and tetraoleoyl cardiolipin (CL). The lipid film was dissolved in Triton buffer to give final concentrations in the assay of 1 mM CL, a specified concentration of DAG, 50 mM Triton X-100, 5 mM MgCl₂, 1 mM EGTA, 100 mM NaCl, 10 mM MOPS (pH 7.2), a protease inhibitor cocktail for use with mammalian cell and tissue culture extracts [Sigma, catalog no. P 8340 at a 1:100 (v/v) dilution], 1 mM DTT, an amount of Ca²⁺ calculated to give 1 nM free calcium, and 3 μ g of MuLK (or the control fusion protein, Synaptic Vesicle Protein 2, amino truncation) in 20% ethylene glycol. The mixture was briefly vortexed and placed in a 30 °C water bath for 10 min. The reaction was initiated by addition of 20 μ L of 2.5 mM [γ -³²P]ATP (250 μ Ci/mL) to give a final volume of 100 μ L. The reaction was generally terminated after 20 min and the phosphatidic acid product extracted and counted as described above.

RESULTS

The activities of several enzymes that phosphorylate DAG were compared in terms of their relative activity against 1,2-DOG versus 2,3-DOG (Table 1). The rate of phosphorylation of 1,2-DAG was found to be linear over 10 min for the DGKs and 20 min for MuLK. The negative control for MuLK, Synaptic Vesicle Protein 2, exhibited less than 10% of the activity of MuLK. In all cases, 1,2-DOG is a better substrate than its enantiomer. However, the relative ability of MuLK to phosphorylate 2,3-DOG is much greater than that for any of the isoforms of DGK used (Table 1). In the case of the DGK isoforms, some of the activity against 2,3-DOG could be a consequence of the presence of \sim 5% 1,2-DOG as an enantiomeric impurity. The relatively higher activity of MuLK against 2,3-DOG compared with the DGKs allowed us to determine the kinetic constants for this enzyme (Figure 1). The measured rates of this enzyme against 1,2-DOG are lower than those previously reported (3); however, the conditions of the assay are not identical, and the enzyme preparation we used had been frozen, stored for several days in this state, and then thawed for use, likely contributing to

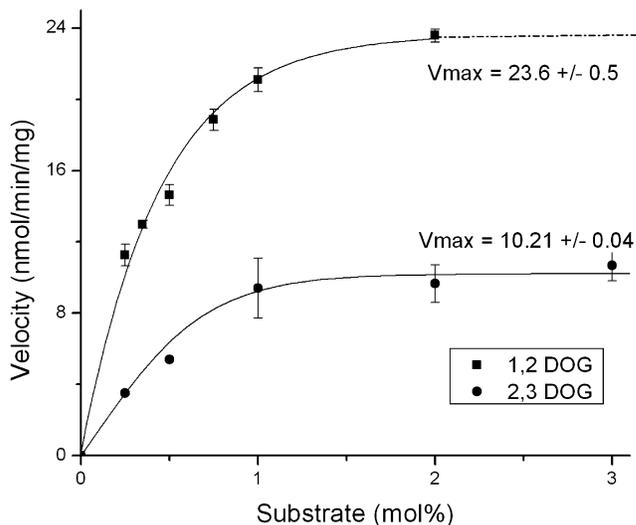


FIGURE 1: Substrate concentration dependence of MuLK-catalyzed phosphorylation of 1,2-DOG and 2,3-DOG: (■) 1,2-DOG and (●) 2,3-DOG. The data are fitted to the Michaelis–Menten equation giving values for the constants V_{max} and K_m for 1,2-DOG of 23.6 \pm 0.5 nmol min⁻¹ mg⁻¹ and 0.309 \pm 0.009 mol %, respectively. The V_{max} and K_m for 2,3-DOG are 10.21 \pm 0.04 nmol min⁻¹ mg⁻¹ and 0.379 \pm 0.002 mol %, respectively. The data represented are averages of two trials of the experiment.

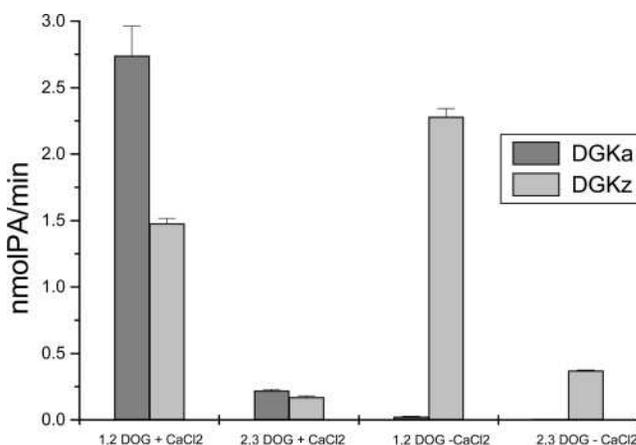


FIGURE 2: Comparison of the activities of DGK α and DGK ζ on 1,2-DOG and 2,3-DOG in the presence and absence of 2.5 mM CaCl₂: DGK α (darker bars) and DGK ζ (lighter bars). Assay conducted with 1 mM EGTA and 5 mM Mg²⁺ at pH 7.2 and 25 °C. Other conditions as described in Experimental Procedures.

the somewhat lower activity observed in this work. The V_{max} and K_m values for 2,3-DOG are 10.21 \pm 0.04 nmol min⁻¹ mg⁻¹ and 0.379 \pm 0.002 mol %, respectively, compared with 23.6 \pm 0.5 nmol min⁻¹ mg⁻¹ and 0.309 \pm 0.009 mol % for 1,2-DOG, respectively. Thus, at V_{max} the activity of MuLK against 1,2-DOG is only \sim 2-fold greater than against 2,3-DOG.

For both DGK α and DGK ζ , there was a much greater activity against 1,2-DOG than 2,3-DOG, both in the presence and in the absence of Ca²⁺ (Figure 2). DGK α is a calcium-dependent enzyme (25) and consequently has much higher activity in the presence of this cation. Ca²⁺ causes a small inhibition of the activity of DGK ζ . This is likely a nonspecific effect caused by the high Ca²⁺ concentration of 2.5 mM that was used. MuLK was assayed in the presence of CL, rather than with the lipids used for the DGK assays. For all of the lipid kinases used in this work, the assay conditions

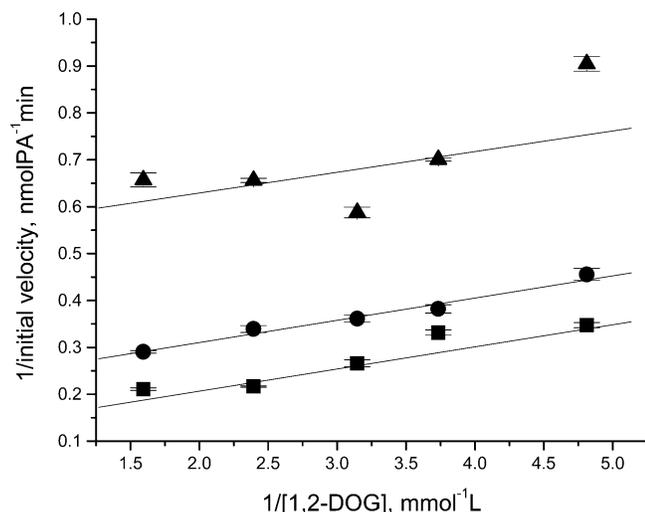


FIGURE 3: Lineweaver–Burk plot for DGK α activity phosphorylation of 1,2-DOG in the presence of 2.5 mM Ca $^{2+}$ and 0 (■), 0.42 (●), or 0.84 mM 2,3-DOG (▲).

were generally chosen to produce high enzymatic activity. One would not anticipate the assay conditions would substantially affect the chiral specificity of the enzymes, as we illustrate in Figure 2 for the presence and absence of Ca $^{2+}$. The Michaelis–Menten constants for the phosphorylation of 2,3-DOG by either DGK α or DGK ζ were not determined because of the low activity observed with this substrate and because some of this activity likely originates from the presence of 1,2-DOG impurities in the 2,3-DOG preparation. However, we did observe that adding a 5- or 10-fold excess of 2,3-DOG over the concentration of 1,2-DOG resulted in a significant inhibition of the rate of production of phosphatidic acid both in the presence and in the absence of Ca $^{2+}$. DGK α was assayed in the presence of 2.5 mM Ca $^{2+}$ and with 0, 0.42, or 0.84 mM 2,3-DOG as a function of 1,2-DOG concentration. Plotting the results as a Lineweaver–Burke plot (Figure 3) indicates that the inhibition of the phosphorylation of 1,2-DOG by 2,3-DOG is characteristic of being uncompetitive. Note that since these are double-reciprocal plots, the spacings of the lines are not proportional to the concentration of inhibitor used. In uncompetitive inhibition, both V_{\max} and K_m are affected, in contrast to competitive inhibition in which only K_m is altered or to noncompetitive inhibition in which only V_{\max} is changed. A similar analysis of the inhibition of DGK ζ phosphorylation of 1,2-DOG by 2,3-DOG also indicates that the inhibition is uncompetitive (Figure 4). The kinetic data were further analyzed to obtain the kinetic constants for the phosphorylation of 1,2-DOG by DGK α and DGK ζ and its inhibition by 2,3-DOG (Table 2).

Unlike DGK α or DGK ζ , the ϵ isoform of DGK does not exhibit competitive inhibition between 2,3-DOG and either 1,2-DOG or SAG (1-stearoyl-2-arachidonoylglycerol) (Figure 5). The activity of DGK ϵ is greater with SAG than with 1,2-DOG as expected due to the arachidonoyl specificity of this isoform. However, addition of 2,3-DOG to either of these two substrates results in increased activity (Figure 5), rather than inhibition as seen with DGK α and DGK ζ . This is likely a result, at least in part, of 2,3-DOG being a weak substrate for DGK ϵ (Table 1). Thus, DGK ϵ differs from DGK α and DGK ζ in that 2,3-DOG does not inhibit the enzyme.

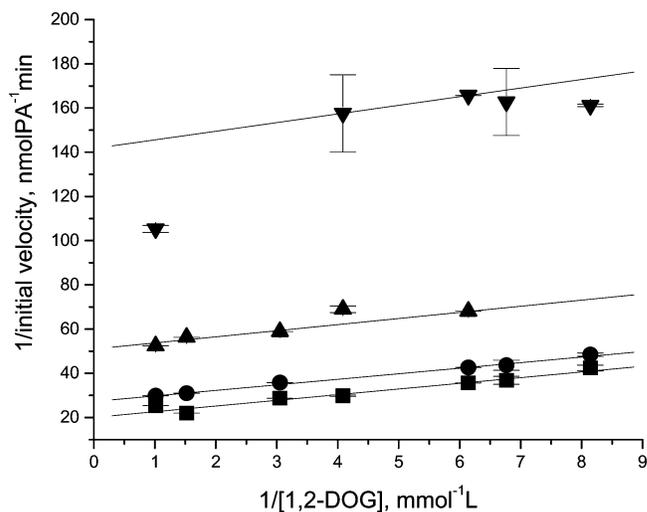


FIGURE 4: Lineweaver–Burk plot for DGK ζ activity phosphorylation of 1,2-DOG in the presence of 0 (■), 0.165 (●), 0.33 (▲), or 0.66 mM 2,3-DOG (▼). Data were combined from six independent experiments and normalized relative to the initial velocity observed in the absence of 2,3-DOG.

Table 2: Kinetic Constants for Phosphorylation of 1,2-DOG by DGK α and DGK ζ and Inhibition by 2,3-DOG

enzyme	1,2-DOG		2,3-DOG
	K_m (mol %)	V_{\max} (nmol of PA/min) ^a	K_i (mol %)
DGK α	0.8 ± 0.3	5.5 ± 0.4	1.7 ± 0.2
DGK ζ	0.52 ± 0.08	0.050 ± 0.002	1.07 ± 0.07

^a The value of V_{\max} is a measure of the maximal rate for the amount of enzyme used, but it is not normalized for the concentration of enzyme, which is not known.

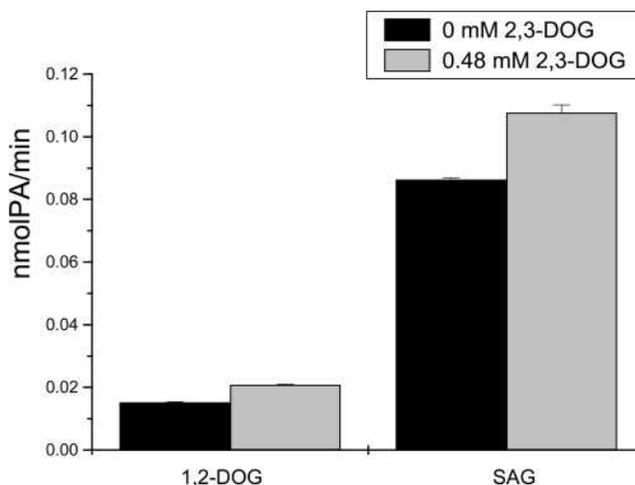


FIGURE 5: Comparison of DGK ϵ activity on 1,2-DOG and SAG in the absence (black bars) and presence of 0.48 mM 2,3-DOG (gray bars). Assay conducted with 0.24 mM 1,2-DOG or SAG and 75 mM OG instead of Triton X-100. Other conditions as described in Experimental Procedures.

DISCUSSION

All three DGK isoforms used in this work exhibited a high degree of chiral specificity for the substrate (Table 1). It had also been observed that protein kinase C was much less activated by 2,3-DAG than by 1,2-DAG, although the binding affinity of 2,3-DAG for protein kinase C was only 4-fold lower than for 1,2-DAG (26). MuLK also phosphorylated 1,2-DOG more rapidly than 2,3-DOG, but with chiral

specificity several-fold lower compared with that of the DGKs.

The chiral specificity of MuLK is not as great as that of the DGKs. Its greater activity with 2,3-DOG may reflect a relationship to prokaryotic lipid kinases that are less specific with regard to the substrate they phosphorylate. As with bacterial lipid kinases, MuLK can also phosphorylate ceramide (3), although ceramides are not substrates for mammalian DGKs. MuLK phosphorylates several different lipid substrates and for that reason has been termed a multiple lipid kinase. MuLK has low substrate specificity and particularly low chiral specificity since both 1,2-DOG and 2,3-DOG are phosphorylated. However, there is partial chiral specificity, since 1,2-DOG is preferred as substrate. Interestingly, archaeobacteria have opposite lipid chiralities compared with those from other species, having their major phospholipids as derivatives of 2,3-DAG (27).

With the DGKs, 2,3-DOG is an inhibitor of the phosphorylation of 1,2-DOG, although it is not a potent inhibitor, requiring a concentration of 2,3-DOG on the order of 5–10-fold higher to cause 50% inhibition of the phosphorylation of 1,2-DOG, depending on the specific isoform and conditions. Analysis of the kinetics indicates that the inhibition is uncompetitive, as indicated by the fact that the Lineweaver–Burke plots with and without the 2,3-DOG inhibitor are parallel to each other for both DGK α (Figure 3) and DGK ζ (Figure 4). Uncompetitive inhibition occurs when the inhibitor binds to the enzyme–substrate complex, but not to the free enzyme. This differs from both competitive inhibition in which the inhibitor binds only to the free enzyme and noncompetitive inhibition in which the inhibitor can bind equally well to the free enzyme and the enzyme–substrate complex. Uncompetitive inhibition is not the type of inhibition one would expect for the enantiomer of a substrate that would *a priori* be anticipated to compete with the substrate for the active site and hence exhibit competitive inhibition kinetics. The results suggest that the binding of 1,2-DOG to the active site induces a conformational change that exposes a site on the enzyme that can bind 2,3-DOG. The DGK isoforms that we used each have two C1 domains. C1 domains are known to generally bind to DAG. However, the C1 domains of DGKs that we tested have not been shown to bind either DAG or phorbol esters *in vitro*. It has been shown that the C1 domains of DGK α are not involved in the binding of DAG to the active site (28). We suggest that the active site of DGK binds DAG with chiral specificity; i.e., it binds only 1,2-DAG and not 2,3-DAG. This process does not directly involve the C1 domains. However, we suggest that the binding of 1,2-DAG to the active site induces a conformational change in the enzyme that makes the C1 domains more accessible to binding DAG in a non-stereospecific manner; i.e., the enzyme can now bind either 1,2-DAG or 2,3-DAG, albeit with lower affinity. This phenomenon results in the uncompetitive inhibition by 2,3-DAG and also causes deviations from Michaelis–Menten kinetics at high concentrations of 1,2-DAG, resulting in a lowering of the maximal rate at high substrate concentrations (unpublished results).

There is an interesting gradation of chiral specificity among the enzymes that were tested. It is known that the chiral specificity of interfacial catalysis is dependent on the structure of the interface (29–31). With the group of

enzymes used in this study, there is a relationship between the substrate specificity and the chiral specificity. Thus, MuLK, which can phosphorylate ceramide as well as DAG, is the least specific enzyme and also the one with the highest activity against 2,3-DOG, showing that it also has low chiral specificity. DGK ϵ is the most specific among the enzymes tested since it not only is specific for 1,2-diacylglycerol but also discriminates among 1,2-diacylglycerols, depending on the nature of the acyl chain. This is the only DGK isoform tested in which 2,3-DOG is neither a good substrate nor an inhibitor. DGK α and DGK ζ are intermediate cases in which 2,3-DOG is a poor substrate, but it can act as an inhibitor. This gradation of properties is not related to the binding affinities of the lipids for these enzymes, which do not differ very much. It is dependent on the specificity, rather than the affinity, of binding.

We have thus shown that DGK α , $-\zeta$, and $-\epsilon$ exhibit a high degree of stereospecificity in catalyzing the phosphorylation of DAG. This would result in the stereospecific formation of PA, which could be further converted to other phospholipid components of the cell membrane that would also be 1,2-diacyl lipids. The stereospecificity of MuLK is much lower, in accord with its designation as a multiple lipid kinase.

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