**In Vivo** Conditions to Identify Prkci Phosphorylation Targets Using the Analog-Sensitive Kinase Method in Zebrafish

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**Abstract**

Protein kinase C iota is required for various cell biological processes including epithelial tissue polarity and organ morphogenesis. To gain mechanistic insight into different roles of this kinase, it is essential to identify specific substrate proteins in their cellular context. The analog-sensitive kinase method provides a powerful tool for the identification of kinase substrates under *in vivo* conditions. However, it has remained a major challenge to establish screens based on this method in multicellular model organisms. Here, we report the methodology for *in vivo* conditions using the analog-sensitive kinase method in a genetically-tractable vertebrate model organism, the zebrafish. With this approach, kinase substrates can uniquely be labeled in the developing zebrafish embryo using bulky ATP-S analogs which result in the thio-phosphorylation of substrates. The labeling of kinase substrates with a thiophosphoester epitepe differs from phosphoesters that are generated by all other kinases and allows for an enrichment of thiophosphopeptides by immunoaffinity purification. This study provides the foundation for using the analog-sensitive kinase method in the context of complex vertebrate development, physiology, or disease.

**Introduction**

Phosphorylation is a protein modification that is essential for almost all aspects of cell biology. Kinases that catalyze this post-translational modification are an abundant group of enzymes with promiscuous substrate specificity and a common requirement for ATP. For this reason, the identification of specific substrate proteins of particular kinases has remained a tedious challenge and traditionally involves *in vitro* phosphorylation assays with candidate substrates. However, *in vitro* assays often generate false-positive results and are inferior to *in vivo* screening conditions in which the kinase of interest localizes within the correct subcellular compartment and is associated with endogenous binding partners that modulate its activity and affinity towards substrate proteins. The analog-sensitive kinase method utilizes *in vivo* conditions for substrate identification but has never been employed in a multicellular model organism [1].

The atypical protein kinase C (αPKC) family consists of serine/threonine kinases with essential cellular functions in cell polarity and organ morphogenesis, cell migration, apoptosis and proliferation (reviewed in [2–5]). Increasing evidence also points at an involvement of αPKCs in the promotion of carcinogenesis *in vitro* and *in vivo* [reviewed in [6]]. Among other proteins, αPKCs are core components of the apical Partition defective 6 (Pard6)-αPKC protein complex which is composed of several PDZ domain containing proteins and is required for the establishment of epithelial apico basal polarity in many systems [reviewed in [4,7]]. The unique N-terminal regulatory domain of αPKCs which contains a Phox Bem1 (PB1) domain mediates direct interactions with the polarity protein Pard6 which in turn modulates αPKC activity, or with the small GTPases Rac1 and Cdc42 [8]. The zebrafish heart and soul locus encodes Prkci, one of two αPKCs expressed in this organism [9,10]. Consistent with a function in apical cell polarity, zebrafish mutants lacking Pckr show defective formation and maintenance of several embryonic epithelia and abnormal heart morphogenesis [9,11,12]. Prkci function in cellular polarity and organ morphogenesis requires its catalytic activity [12].

To date, only a small number of substrate proteins of Prkci in the context of cellular polarity, proliferation control or apoptosis have been identified in any organism, and the molecular
mechanisms of their interaction with aPKCs have been convincingly demonstrated for only a few of them [13–19]. In addition to its auto-phosphorylation [3], potentially relevant substrate proteins of aPKC activity in the context of cellular polarity are Par3 [17,20,21], Numb [22,23], Miranda [24], Frizzled 1 [25], Partner of inscutable [26], and GSK-3β [9]. To further elucidate the mechanistic relevance of aPKCs during development and in various cell biological processes it is necessary to identify phosphorylation targets in an unbiased manner and under in vivo conditions.

We have established conditions for a chemical genetics screen using the analog-sensitive kinase method to identify phosphorylation targets of Prkci during zebrafish development. This methodology opens the way for the identification and functional characterization of specific substrates in their normal subcellular context which is essential for a mechanistic understanding of how Prkci affects divergent cellular processes.

Results

Design of an Analog-sensitive Prkci

We established a screening approach with the aim to identify Prkci phosphorylation targets in a multicellular model organism. The straightforward screening method using analog-sensitive kinases utilizes an environment that is similar to the in vivo state of the kinase. In principle, the method is based on engineering a mutant kinase that accepts bulky ATP or ATPγS analogs such as N6-benzyl ATP or N6-benzyl ATPγS. The ATP analog-sensitive kinase is generated by replacing a large hydrophobic group within the ATP binding pocket (the “gatekeeper” residue) with a smaller residue thereby enlarging the binding pocket which allows the kinase to accept bulkier ATP analogs (Fig. 1A). The specificity of this approach has been demonstrated for various kinases, e.g. by utilizing a modified v-Src, c-Raf-1, or AMPKα2 for the identification of novel substrates [1,27,28].

To identify an ATP binding site “gatekeeper” residue within the Prkci ATP binding pocket, we selected suitable residues for site-directed mutagenesis based on the high evolutionary conservation of the ATP binding site in different protein kinases, including v-Src [1] and c-Raf-1 [28] that had successfully been engineered to utilize N6-benzyl ATP. The comparison of the primary sequence of Prkci, c-Src, and c-Raf-1 kinase domains suggested Val190 and Ile316 of Prkci to be the most likely “gatekeeper” residues and therefore to be the most suitable targets for site-directed mutagenesis (Fig. 1B).

Mutant PrkciI316A has Normal in Vivo Biological Activity

One stringent requirement for an analog-sensitive kinase is the conservation of its biological properties which includes normal in vivo functionality and substrate specificity. We therefore tested whether the PrkciWT or Prkci316A mutants with altered ATP binding pockets had normal biological activity. Loss of Prkci has well-characterized epithelial and organ morphogenesis defects that involve cardiac malformations and a defective neuroepithelium [9,11,12]. In functional rescue experiments, we co-injected at the one-cell stage mRNA encoding either PrkciWT or one of the two mutant Prkci proteins together with an antisense oligonucleotide morpholin (MO) for knockdown of endogenous Prkci. Whereas expression of Prkci316A allowed normal cardiac development (63% of prkci morphant embryos rescued, n = 183) which was almost as efficient as PrkciWT expression (83% of prkci morphants rescued, n = 166), the Prkci316A mutant was not biologically active based on the appearance of prkci morphant cardiac phenotypes among all injected embryos (Fig. 2A) [9].

Because the Prkci316A mutant was biologically fully functional within the heart, we anticipated that this mutant kinase should correctly localize within myocardial cells. Indeed, expression by injection at the one-cell stage of mRNA encoding Myc-tagged Prkci1316A resulted in the correct localization of the mutant protein to the cell membrane, similar to Myc-tagged PrkciWT or endogenous Prkci (Fig. 2B). That overexpression of PrkciWT or Prkci316A did not cause any ectopic phenotypes strongly suggests substrate specificity (see below). Together, our results indicated that Prkci316A is biologically functional and predominantly localizes to the correct subcellular compartment at the cell membrane, which makes this mutant kinase a strong candidate for a chemical genetic screen.

Mutant PrkciI316A can use Bulk ATP Analogs

We next tested whether Prkci316A could utilize bulky ATP analogs by assaying the phosphorylation efficiency and specificity of several alkylated ATPγS analogs in in vitro kinase assays. ATPγS was utilized instead of regular ATP to ensure a transfer of a phosphorothioate moiety to the phosphoacceptor hydroxyl groups of respective substrates. The substitution of sulfur in place of oxygen generates unique thiophosphorylated epitopes that, when alkylated with p-nitrobenzyl mesylate (PNBM), generate thiosphoester epitopes which can be recognized by a specific monoclonal antibody [29,30]. Using the baculovirus system in Sf9 insect cells, we produced the recombinant kinases and first confirmed that PrkciWT and Prkci316A could utilize ATPγS to phosphorylate Myelin Basic Protein (MBP) as substrate and that this modification could efficiently be detected with the anti-thiosphoester antibody (Fig. 3). However, whereas PrkciWT accepted ATPγS, it could not utilize any of the tested N6-alkylated ATPγS analogs (N6-benzyl-, N6-phenethyl-, or N6-cyclopropyl-ATPγS) [30] as assessed on Western blot upon the in vitro kinase assay. In contrast, Prkci316A most efficiently utilized N6-benzyl ATPγS (Fig. 3) whereas the other two bulky ATPγS analogs were apparently not efficiently utilized (data not shown). Taken together, Prkci316A had a normal biological function in the in vivo context and exerted catalytic activity using a bulky N6-benzyl-ATP analog. Hence, Prkci316A fulfilled the basic requirements required to identify Prkci phosphorylation targets.
Evidence for PrkciI316A-mediated Thiophosphorylation in the Zebrafish Embryo

Two principal methods have been used for the enrichment of thiophosphorylated proteins in in vitro phosphorylation assays and in cell culture systems but not yet in any model organism. The "covalent capture" approach is based on the enrichment of thiophosphate-tagged substrates with iodoacetyl-agarose and subsequent analysis by mass spectrometry [31]. An alternative approach is based on "immunoaffinity purification" enrichment using the anti-thiophosphoester antibody, followed by mass spectrometry of enriched peptides [27,30]. Both methods require the utilization of ATPcS analogs for the unique labelling of substrate proteins.

One preeminent challenge of using ATPcS analogs in in vivo approaches is the potential toxicity of thiophosphates since such protein modifications cannot be removed by phosphatases. We first tested the toxicity of N6-benzyl ATPcS by injecting different concentrations (1 nL injection volume) into wild-type embryos and found that a concentration of 200 μM N6-benzyl ATPcS was the maximal concentration that could be injected into one-cell stage embryos without affecting development (200 μM: 93.3% of embryos developed normally, n = 45; 250 μM: 47.8% of embryos developed normally, n = 23; 500 μM: 37.2% of embryos developed normally, n = 43). We next tested the feasibility of applying this approach in the zebrafish embryo by optimizing the conditions for introducing N6-benzyl ATPcS together with mRNA encoding PrkciI316A in cardiomyocytes detected with an anti-Myc antibody. Images are confocal reconstructions of single Z-stack sections of embryonic hearts marked by the transgenic reporter Tg[cmlc2:GFP]twu3 at 28–30 hpf. Expression of exogenous HisMyc-PrkciWT or HisMyc-PrkciI316A in cardiomyocytes reveals that both recombinant proteins localize to the cell membrane.

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Figure 3. Mutant PrkciI316A uses bulky N6-benzyl ATPγS. Kinase reaction with Myelin Basic Protein (MBP) and ATPγS or N6-benzyl ATPγS (6-bn-ATPγS), followed by PNBM alkylation. In comparison, only mutant PrkciI316A efficiently utilizes N6-benzyl ATPγS to thiophosphorylate MBP. Labeled MBP is detected by Western blot analysis with rabbit monoclonal anti-thiophosphoester antibody (α-thioP).

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expressing embryos developed normally, n = 320), which was comparable with embryos co-injected with N$^6$-benzyl ATPγS and mRNA encoding PrkciWT (96.5% of embryos developed normally, n = 261), or with non-injected control embryos (96.7% of embryos developed normally, n = 390). Therefore, N$^6$-benzyl ATPγS in the range of physiological ATP levels is compatible with normal zebrafish embryogenesis.

To assess whether thiophosphorylation had occurred in the developing zebrafish embryo, such in vivo thiophosphorylated 8 hpf extracts were alkylated using PNBM, resolved by SDS-PAGE, and Western blots probed with the anti-thiophosphoester antibody. This analysis revealed that thiophosphorylation of substrates had indeed occurred in the zebrafish embryo and that PrkciI316A had catalyzed the selective labelling of at least one putative substrate (Fig. 4B).

Discussion

This study outlines the methodology required for an in vivo screening approach using an analog-sensitive kinase in a multicellular model organism. Our work demonstrates the conditions for in vivo thiophosphoester labeling of substrates using an analog-sensitive kinase and bulky N$^6$-benzyl ATPγS analogs. Injection of physiological levels of bulky N$^6$-benzyl ATPγS does not interfere with zebrafish development even though thiophosphorylations are largely irreversible. Viability of zebrafish embryos under such conditions indicates that only a fraction of substrate proteins is modified by the analog-sensitive kinase and such in vivo thiophosphorylations are detectable on Western blots. That thiophosphorylations are also detected in PrkciWT samples is due to unspecific utilization of N$^6$-benzyl ATPγS by other enzymes [31] and to the partial degradation of N$^6$-benzyl ATPγS to ATPγS which can be utilized by other kinases. These contaminations with unspecific thiophosphorylations highlight the need to immunopurify embryonic extracts and to perform comparative mass spectrometric analyses for substrate identification.

The method for the enrichment and identification of novel putative kinase targets by immunoffinity purification with an anti-thiophosphoester antibody is well-established [27,30]. Combining this methodology with the working protocol outlined in our study will soon provide unprecedented insight into kinase signaling in multi-tissue encompassing developmental processes, the regulation of different physiological conditions, or in disease processes involving aberrant kinase signaling. Taken together, our work provides the ground for similar approaches using the analog-sensitive kinase method in this and other multicellular model organisms.

Materials and Methods

Fish Maintenance and Stocks
Zebrafish were maintained at standard conditions [32]. Embryos were kept in egg water (60 mg/ml Instant Ocean Sea Salts, Aquarium Systems Inc., USA) and staged at 28.5°C [33]. The following fish strains were used: AB (wild-type), Tg[cmlc2:GFP]twu34 [34].

Figure 4. Thiophosphorylation of substrate proteins by PrkciI316 in the zebrafish embryo. (A) Schematic diagram of the in vivo labeling method for the selective labeling of PrkciI316A substrates during zebrafish development. (B) In vivo thiophosphorylation in zebrafish embryos injected at the one-cell stage with 200 μM N$^6$-benzyl-ATPγS (6-bn-ATPγS) and mRNA encoding either PrkciWT or PrkciI316A (AS). Western blot analysis with rabbit monoclonal anti-thiophosphoester (α-thioP) CS1-8 antibody (Epitomics) of 80% epiboly (6–8hpf) samples alkylated with 2.5 mM PNBM reveals a selectively labeled protein in the PrkciI316A (AS) sample (asterisk). doi:10.1371/journal.pone.0040000.g004
RNA and Antisense Oligonucleotide Morpholino Injections

Constructs were transfected using the SP6 mMessage mMACHINE kit (Ambion). Tg[cmlc2:GFP] embryos were injected with 2.5 ng of pcke MO [12]. To rescue experiments 100 pg of mRNAs were injected. The heart morphology was assessed at 24 hpf. Data presented are the means of at least 2 independent experiments. For in vivo labeling, 200 pg of mRNA encoding HisMyc-PrkciWT or HisMyc-PrkciI316A mRNA were injected at the one-cell stage.

The antiense oligonucleotide morpholino was purchased from Gene Tools, LLC, USA. pcke MO (5’→3’): TGTCGCCGAGCTGGGCCATATGGA [12].

DNA Constructs and Site-directed Mutagenesis

Both constructs encoding wt and mutant forms of Prkci were produced by PCR amplification from a full length cDNA template, pCS2+ HisMyc:prkci [12]. Site-directed mutagenesis was performed using the QuickChangeTM XL Site-Directed mutagenesis kit (Stratagene). Primer sequences are available upon request.

Protein Extraction from Zebrafish Embryos

Zebrafish embryos protein extraction was performed as previously described [35]. Embryos were dechorionated with pronase solution in E2 medium in Petri dishes coated with 1% agarose. After washes with E2 medium, embryos were transferred to 1.5 ml tubes. The yolk was disrupted by pipetting with a 1 ml pipet and vortexing for 30 seconds at 1100 rpm in deyolking buffer. Embryos were pelleted several times after washes in washing buffer at 3000 rpm for 30 seconds. Pelleted embryos were homogenized in the appropriated lysis buffer depending on the following experiment.

Recombinant Protein Expression in Insect Cells

To express recombinant PrckiWT or PrkciI316A in Sf9 insect cells (Sigma), Bac-to-Bac® Baculovirus Expression System (Invitrogen) was used according to the manufacturers' protocol. HisMyc:prkci WT and HisMyc:prkciI316A cDNAs were cloned into pFastBacTM1. Primer sequences are available upon request.

Whole-mount Immunohistochemistry and Confocal Imaging

Whole-mount antibody stainings were performed as previously described [9]. The following antibodies were used: rabbit anti-aPKC (1:100, Santa Cruz SC-216), mouse anti-Myc (1:200, Invitrogen), goat anti-rabbit RRX (1:250, Jackson ImmunoResearch), goat anti-mouse Cy5 (1:250, Jackson ImmunoResearch Laboratories), goat anti-mouse Cy5 (1:250, Jackson ImmunoResearch Laboratories). For imaging, samples were embedded in SlowFade® Gold antifade reagent (Invitrogen) under a binocular microscope (Leica). Confocal images were obtained with a Zeiss LSM 510 Meta confocal microscope using 40X or 63X objectives. Zeiss LSM 510 software was used to record images. Images were processed using Photoshop (Adobe).

In vitro kinase Assay

For in vitro kinase assays 50 pg of MBP were incubated at 30°C for 30 minutes with 5 pg of recombinant HisMyc-PrkciWT or HisMyc-PrkciI316A and 500 μM ATPγS or N-benzyl ATPγS (BioLog, B072-05) in kinase buffer [25 mM Tris-HCl, pH 7.5, 25 mM NaCl, 10 mM MgCl2, 1 mM EGTA, protease inhibitor cocktail (Roche)]. The other bulky ATP analogs (N6-phenethyl-ATPγS, N6-cyclopentyl-ATPγS) were generated as described [30]. The kinase reaction was stopped by adding 4x SDS loading buffer and boiling at 95°C for 5 minutes. Samples were analyzed by Western blot using the following antibodies: mouse anti-Myc (1:1000, Invitrogen), anti-thiophosphoester rabbit polyclonal antibody (1:5000 Epitomics), rabbit anti-GAPDH (1:1000), goat anti-mouse HRP (1:5000, Jackson ImmunoResearch), goat anti-rabbit HRP (1:10000, Jackson ImmunoResearch).

In Vivo Thiophosphorylation in Zebrafish Embryos

For in vivo thiophosphorylation 200 pg of mRNA encoding HisMyc-PrkciWT or HisMyc-PrkciI316A were injected into the yolk at the one-cell stage together with approximately 1 nL of 200 μM 6-benzyl ATPγS. Embryonic protein extracts were prepared at 8 hpf, and pelleted embryos were homogenized in RIPA buffer. Alkylation was performed for 2 hours at RT with 2.5 mM PNBM [30]. Samples were analyzed by Western blot using anti-thiophosphoester rabbit monoclonal C51-8 antibody (1:5000 Epitomics).

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Author Contributions

Conceived and designed the experiments: ECU NH MK MS SAS. Performed the experiments: ECU NH MK SD. Analyzed the data: ECU SAS. Contributed reagents/materials/analysis tools: KS JJA. Wrote the paper: ECU SAS.

References


