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Brief Article

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Highly potent and isoform-selective dual-site-binding tankyrase/Wnt signaling inhibitors that increase cellular glucose uptake and have anti-proliferative activity.

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KEYWORDS: Tankyrase, PARP, Glucose uptake, Wnt signaling, Crystal structure, Insulin.

ABSTRACT: Compounds **13** and **14** were evaluated against eleven PARP isoforms to reveal that both **13** and **14** were more potent and isoform-selective towards inhibiting tankyrases (TNKSs) than the "standard" inhibitor **1** (XAV939)⁵, *i.e.* $IC_{50} = 100 \text{ pM } vs$. TNKS2 and $IC_{50} = 6.5 \mu M vs$. PARP1 for **14**. In cellular assays, **13** and **14** inhibited Wnt-signaling, enhanced insulin-stimulated glucose uptake and inhibited the proliferation of DLD-1 colorectal adenocarcinoma cells to a greater extent than **1**.

INTRODUCTION

Tankyrases (TNKSs) are members of the poly(ADP-ribose)polymerase (PARP) family of seventeen enzymes that use NAD⁺ as a substrate to transfer ADP-ribose units to target proteins.¹ There are two human isoforms, TNKS1 and TNKS2. Target proteins include telomere repeating binding factor-1 (TRF1),^{2,3} nuclear mitotic apparatus protein (NuMA)⁴ (essential for the resolution of chromatids during mitosis) and axin, the limiting component of Wnt / β-catenin signaling.⁵ Increased Wnt signaling correlates with the overexpression of TNKSs in several human cancers.⁶⁻⁹ Inhibition of TNKSs is reported to lead to stabilization of axin and decreased nuclear β-catenindriven proliferation of cancer cells.¹⁰ Epidemiological studies show that patients with Type-2 diabetes are at higher risk of developing site-specific cancers¹¹ but the precise mechanisms that link diabetes to cancer remain unclear. The axin-TNKS-KIF3A complex is required for insulin-stimulated translocation of GLUT4 to the cell memembrane.12 Insulin-regulated aminopeptidase (IRAP) is also a binding partner and target protein of TNKSs.¹³ Together, IRAP and TNKSs can enhance insulinstimulated exocytosis of GLUT4, which could result in increased uptake of glucose.13 TNKS-knockout mice display increased sensitivity to insulin and reduced adiposity and pan-PARP inhibitors have been used to investigate the role of TNKSs in studies on the translocation of GLUT4.¹⁴ Inhibitor 1 (XAV939)⁵ (Fig. 1) has been extensively used as a tool to inhibit TNKSs and of Wnt / β-catenin signaling⁵ but lacks the required isoform-selectivity to avoid off-target effects. Related inhibitors of TNKSs include flavones,¹⁵ 2-arylquinazolin-4ones such as **2**,^{16,17} isoquinolin-1-ones¹⁸ and aryltetrahydronaphthyridinones, which maintain a classical binding mode in the nicotinamide-binding site.¹⁹ Compound **3** (IWR-1)²⁰ (Fig. 1) is an inhibitor of the Wnt signaling cascade through inhibiting TNKSs, binding only to the adenosine-binding site.²⁰ The norbornane of **3** forces a conformational change of Tyr¹⁰⁵⁰ (TNKS2 numbering), allowing the quinoline of **3** to π -stack with His¹⁰⁴⁸ within this site.²¹ Our previous reports of novel inhibitors include 2-aryl-8-methylquinazolin-4-ones with 4'-large or electron-withdrawing substituents (*e.g.* **2**) to provide inhibition of TNKSs (IC₅₀ in the low nM range) and of Wnt / β -catenin signaling.^{16,17} Some known inhibitors bind in both the nicotinamide-binding site and the adenosine-binding domain,^{22,23} although the increases in potency *vs.* **1** were modest.



Figure 1. Examples of previously studied inhibitors of TNKSs 1, 2 (nicotinamide-site binders) and 3 (adenosine-site binder). Inhibitor 2 is shown with locant numbers.

Here, we report the rational design and evaluation of advanced inhibitors (13, 14) which maintain the 8-methylquinazolin-4-

one core and carry extensions at the 2-position to induce conformational change and binding to the adenosine-binding site, leading to a step-change in potency and isoform-selectivity. These highly potent and isoform-selective inhibitors have potential as excellent molecular probes applicable to research on diabetes and cancer.

RESULTS AND DISCUSSION

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Modeling. Structural alignment of the co-crystal structures of 2 (PDB 4UFU) and 3 (PDB 3UA9) with TNKS2^{17,21} provided initial insights towards the design of 13 and 14. The quinazolinone of 2 binds in the nicotinamide-binding site, making the expected H-bonds with Ser¹⁰⁶⁸ and Gly¹⁰³² and π -stack with Tyr¹⁰⁷¹ (TNKS2 numbering). The quinoline of **3** is located in the adenosine-binding site, making a π -stack with His¹⁰⁴⁸ (TNKS2 numbering). Features binding at each site were linked to create chimeric compounds 13 and 14, which combine important H-bonds and stacking interactions at both binding sites. Modeling of 13 and 14 into the active site of TNKS1 (PDB 4I9I)²³ predicted that the designed compounds could bind to the pockets in the intended way and that the length and nature of the linker were appropriate (Fig. 2). The quinazolin-4-one core could bind in the nicotinamide-binding site to make the classical H-bond and π -stacking interactions. Compounds 1 and 2 contain a 2-aryl group, which is shown to occupy a hydrophobic cavity. Modeling of 13 into TNKS1 suggests that the chosen linker could allow Tyr¹²⁰³ to move towards the nicotinamidebinding site and decrease the volume of the hydrophobic cavity. However, this shrinkage of the pocket could still allow the propanamide linker to thread through. The modeling study reveals that the linker could interact further with the protein, in that the C=O of the propanamide linker is appositely located to H-bond with the backbone NH of Tyr¹²¹³. Moreover, the central benzene ring and the quinoline of 13 are predicted to cause movement of His¹²⁰¹ of the adenosine-binding site to place its imidazole appropriately for π -stacking with the quinoline. We have previously reported that an 8-Me group enhances inhibitory activity in the simple 2-arylquinazolinones^{16,17} and related 3-arylisoquinolinones,¹⁸ we also incorporated the 8-Me in 14, to test if it would still make a contribution in these advanced dual-sitebinding compounds (Fig. 2).



Figure 2. Model of **13** docked into the structure of TNKS1 (PDB code 4I9I).²³ The protein is shown in pink and **13** in cyan. Key H-bonds shown as grey dashed lines.

Chemical Synthesis. The synthesis of target compounds (Sch. 1) began by acylation of 8-aminoquinoline **4** with 4-nitrobenzoyl chloride to give **5**, followed by transfer hydrogenation to provide amine **6**. Anthranilamides **7** and 8^{24} were acylated with ethyl 4-chloro-4-oxobutanoate to provide **9** and **10**. One-pot cyclisation and hydrolysis in aqueous base led to the quinazolinonepropanoic acids 11 and 12. Careful optimization of the coupling conditions was required to join 11 / 12 with 6; simultaneous addition of the activating agent (CDI) and quinazolinones 11 / 12 to 6 was essential to provide the candidate dualsite-binding inhibitors 13 and 14 in modest yields.



Scheme 1. Synthesis of **13** and **14**. *Reagents and conditions*: i) nitrobenzoyl chloride, pyridine, THF, 16 h, Ar; ii) $^{+}NH_{4}$ HCO₂⁻, 10% Pd/C, DMF/MeOH (2:1), 2 h, Ar; iii) EtO₂CCH₂CH₂COCl, pyridine, THF, 16 h; iv) aq. NaOH (0.5 M), 60°C; v) 6, DMF, Prⁱ₂NEt, carbonyldiimidazole, 72 h, Ar.

Biochemical evaluation. The target compounds 13 and 14 were evaluated in vitro for inhibition of TNKS1 and TNKS2 and counterscreened against eleven PARP isoforms, including the major isoform PARP1 (Table 1). Known inhibitors 1 and 3 were also examined as standards against PARP1, PARP2, TNKS1 and TNKS2. The nicotinamide-site binder 1 showed IC50 values in the low nanomolar range for inhibition of TNKS1 and TNKS2, which were similar to those reported by Huang et $al.^{5}$ However, although 1 showed reasonable selectivity for TNKS2 vs. PARP1 (131-fold), other comparisons called into question the use of this agent as a selective inhibitor (TNKS1 vs. PARP1 25-fold; TNKS1 vs. PARP2 4.1-fold). Compound 3, which binds in the adenosine-binding site, had moderate activity against TNKS1 and TNKS2 (IC50 = 343 nM and 31 nM, respectively) and did not inhibit PARP1 or PARP2 up to 10 µM. These data are again consistent with earlier evaluations of the selectivity of this agent. Huang et al.⁵ reported IC₅₀ (TNKS2) = 56 nM and selectivity vs. PARP1 and PARP2 > 300-fold, while Narwal *et al.* confirmed the selectivity of **3** with $IC_{50} = ca$. 100 μ M (PARP1) and IC₅₀ = ca. 35 μ M (PARP2).²¹ Thus binding at the adenosine site has potential for greater selectivity for TNKSs vs. other PARPs, although this may not give high potency as the sole binding site.

Intermediate **6**, containing the putative adenosine-site-binding benzamidoquinoline, was evaluated for ability to bind in the absence of the anchoring quinazolin-4-one but it failed to inhibit any of the isoforms. This shows that the norbornane of **3** is essential, interacting with Tyr^{1203} to modify the geometry of the adenosine-binding site to accept the benzamidoquinoline.

The candidate dual-site inhibitors **13** and **14** were shown to be extremely potent and isoform-selective inhibitors of TNKSs, inhibiting TNKS2 in the pM range and thus they are both

Compound	1	3	6	11	12	13	14
PARP1	854 nM	>100000 nM ^a	>100000 nM ^a	6700 nM	1000 nM	8230 nM	6500 nM
	(6.07 ± 0.13)			(5.18 ± 0.17)	(5.18 ± 0.17)	(5.08 ± 0.12)	(5.19 ± 0.06)
PARP2	141 nM	>100000 nM ^a	b	125 nM	145 nM	6900 nM	11600 nM
	(6.85 ± 0.08)			(6.90 ± 0.04)	(6.84 ± 0.12)	(5.16 ± 0.12)	(4.94 ± 0.05)
PARP3						40000 nM	45000 nM
						(4.40 ± 0.14)	(4.34 ± 0.10)
PARP4						69000 nM	65000 nM
						(4.16 ± 0.10)	(4.19 ± 0.07)
TNKS1	34 nM	343 nM	>100000 nM ^a	>100000 nM ^a	>100000 nM ^a	9.1 nM	5.1 nM
	(7.47 ± 0.23)	(6.46 ± 0.09)				(8.04 ± 0.05)	(8.29 ± 0.27)
TNKS2	6.5 nM	31 nM	>100000 nM ^a	>100000 nM ^a	>100000 nM ^a	0.20 nM	0.10 nM
	(8.19 ± 0.09)	(7.51 ± 0.10)				(9.69 ± 0.17)	(10.0 ± 0.05)
PARP10						>100000 nM ^a	>100000 nM ^a
PARP12						>100000 nM ^a	>100000 nM ^a
PARP14						>100000 nM ^a	>100000 nM ^a
PARP15						>100000 nM ^a	>100000 nM ^a
PARP16						>100000 nM ^a	>100000 nM ^a
Wnt	220nM	136 nM ^c				29 nM	37 nM
	(6.66 ± 0.10)					(7.54 ± 0.05)	(7.43 ± 0.06)
^{<i>a</i>} Limited by solubility. ^{<i>b</i>} Empty cells indicate not determined. ^{<i>c</i>} Determined previously. ²³							

Table 1. IC_{50} (pIC₅₀ ± standard error) values for inhibition of TNKS1, TNKS2 and PARP isoforms in biochemical assays and for inhibition of Wnt signaling in a cellular assay.

considerably more potent than the "standard" inhibitor 1 and the adenosine-site-binder 3. This increase in potency of inhibition of the TNKSs for 13 and 14 was not accompanied by an increase in activity against other members of the PARP family (Table 1). In particular, 13 and 14 showed very weak activity against PARP1 and PARP2 (IC₅₀ >> 6 μ M), leading to exquisite isoform-selectivity. Inhibitor 13 is 4.1×10^4 -fold selective for TNKS2 vs. PARP1 and 3.5×10^4 -fold selective for TNKS2 vs. PARP2. Similarly, **14** is 6.5×10^4 -fold selective for TNKS2 vs. PARP1 and 11.6×10^4 -fold selective for TNKS2 vs. PARP2. The somewhat weaker potency of these agents against TNKS1 corresponds to selectivities for TNKS1 vs. PARP1 and PARP2 in the range $1-2.3 \times 10^3$ -fold. Thus exploiting dual-site binding with an appropriate linker makes a step-change in potency and provides isoform-selectivity with this potency. Compound 14 is approximately twice as potent as 13 against both isoforms, confirming the moderate advantage of the 8-Me on the quinazolinone core.^{16,18,17} Intermediates 11 and 12, carrying only a propanoic acid at the quinazolinone 2-position, were evaluated to explore the contribution of the quinazolinone-CH2CH2CO unit towards potency and selectivity; both showed no inhibition of TNKSs. We have previously shown that a 2-aryl group is required for potent inhibition of TNKSs; this requirement is thereby reinforced for inhibitors that bind only as mimics of nicotinamide.¹⁶⁻¹⁹ However, 11 and 12 do inhibit PARP1 and PARP2. Previously, we showed that polar groups at the 4'-position of 2-arylquinazolin-4-ones decreased selectivity for TNKSs, in that inhibition of PARP1 was enhanced;¹⁶⁻¹⁸ therefore, the 2-propanoic acid of 11 and 12 is well suited to interact with the corresponding region of protein of PARP1 that contains hydrophilic residues. Furthermore, 11 and 12 displayed moderately potent and selective inhibition of PARP2 (54- and 6.9-fold, respectively, vs. PARP1), results which place 11 amongst the most PARP2-selective agents known.²⁵ Therefore, 11 and 12 provide a new scaffold towards the development of novel PARP2-selective inhibitors.

X-ray crystallography. To rationalize the potency and iso-

form-selectivity of 13 and 14, crystal structures of the compounds in complex with TNKS2 catalytic domain were solved (Supplementary information). The guinazolinone binds to the nicotinamide pocket as designed and forms interactions with the protein similar to those of 2 (PDB code 4UFU).¹⁷ The stacking interaction with Tyr¹⁰⁷¹ and the H-bonds with Gly¹⁰³² and Ser¹⁰⁶⁸ are preserved (Fig. 3). Binding of 3 causes opening of the active-site loop and moves His¹⁰⁴⁸ away from the binding pocket.²¹ Similar changes are observed in the crystal structures of the complexes of 13 and 14 and the quinoline binds to form an induced adenosine-binding pocket. Importantly, the H-bonds to Tyr¹⁰⁶⁰ and to Asp¹⁰⁴⁵, observed in adenosine-site inhibitors,²⁶ are both present in the TNKS2 structures containing 13 and 14. The central phenyl ring adopts slightly different conformations in the experimental crystal structures of 13 and 14, indicating flexibility in the hydrophobic surface at this site. A recent dualsite binding inhibitor binds to the catalytic domain in a very similar manner (IC₅₀ = 2 nM vs. TNKS2)²³ but does not create as efficient π -stacking interaction with His¹²⁰¹ as does the electron-poor bicycle of 13 and 14. This may explain why compounds 13 and 14 exhibit such high inhibitory activity towards TNKSs. Unlike PARP1 and PARP2, TNKSs do not contain an α -helical regulatory domain. This domain packs against the NAD⁺-binding groove and the interactions at the adenosine site contribute to the potent selectivity of the adenosine-site binders. The extreme isoform-selectivity of 13 and 14 can be rationalized, similarly to 3, to be mainly due to the quinoline in the adenosine-binding pocket and unfavorable interactions with the charged residues present in PARP-1 and PARP-2.17,21





Figure 3. Crystal structure of A) TNKS2-13 (PDB code 5FPF) and B) TNKS2-14 (PDB code 5FPG). Hydrogen bonds are shown in dashed lines and the electron density (2mFo-DFc) is contoured at 1 Å around the ligand.

Inhibition of Wnt signaling in TCF/LEF reporter-HEK293 cells. The intracellular activity and potency of 13 and 14 was evaluated in a functional assay using a TCF/LEF Reporter-HEK293 cell line (BPS Bioscience, catalog #60501).²⁷ Upon extracellular Wnt signals, β-catenin is stabilized and associates with TCF/LEF transcription factors, activating transcription.5.27 TNKSs control the stability of the β-catenin destruction complex and inhibition is expected to stabilize the destruction complex and thus lower the levels of β-catenin.⁵ The TCF/LEF Reporter-HEK293 cell line is used to measure this interference with this pathway. Both 13 (IC₅₀ = 29 nM) and 14 (IC₅₀ = 37 nM) were shown to be extremely effective and potent cellular inhibitors of Wnt / β-catenin signaling, confirming their uptake into cells and their activity therein (Table 1). Thus 13 and 14 are *ca*. $10 \times$ more potent in cells than the standard inhibitor 1, reflecting the greater potency of the dual-site inhibitors in vitro. Cell viability was monitored with a light microscope; 13 and 14 were not cytotoxic in this assay.

Anti-proliferative activity towards DLD-1 human colon carcinoma cells. Aberrant Wnt signaling is found in > 90% of colorectal cancers, owing to mutation in the APC protein which is a component of the β -catenin destruction complex.⁶ Compound 1 has been reported to have anti-proliferative activity against DLD-1 human colon cancer cells but only under serum-deprived conditions.^{5,28} Using a colony-forming assay, 13 and 14 were shown to inhibit formation of colonies of DLD-1 cells even under normal-serum conditions (Fig. 4) at 100 nM and 1.0 μ M, conditions under which 1 was inactive. This observation again reflects the greater potency of 13 and 14 *in vitro* and in cells.



Figure 4. Upper: Exemplary image of DLD-1 colony forming assay (1000 cells/well) with 1, 3, 13 and 14 (0 μ M (control with 1% DMSO v/v only), 1.0 μ M and 100 nM). Lower: Histogram of data from assay. 1, 3, 13 and 14 (n = 3).

Insulin-stimulated glucose uptake. The axin-TNKS-KIF3A complex is stabilized through inhibition of TNKS.¹² Ablation of expression of TNKSs has been reported to upregulate GLUT4 at the post-transcriptional level, potentially increasing uptake of glucose into adipocytes.¹⁴ To address this pharmacologically, 13 and 14 were examined for their ability to enhance insulinstimulated uptake of glucose. 3T3-L1 Adipocytes were treated with 13 and 14 in the presence of insulin (100 nM).²⁹ Compound 1 was used for comparison as the current "standard" TNKS inhibitor. The insulin-stimulated uptake of radiolabeled 2-deoxy-D-glucose into the cells was measured. The weaker TNKS inhibitor 1 had no effect on insulin-stimulated glucose uptake in comparison to the insulin-only control. The slight decrease in non-stimulated glucose uptake in presence of 1 (1.0 μ M) was not significantly different from control. Non-stimulated glucose uptake in presence of 13 and 14 (1.0 μ M) was not significantly different from control. In comparison to insulin only and with 4 12

1, both **13** and **14** significantly further increased insulin-stimulated glucose uptake. Glucose uptake increased by ca. 40% and 20% using 100 nM and 1.0 μ M of **13**, respectively. Insulinstimulated uptake of glucose increased by ca. 20% by **14** at 100 nM and 1.0 μ M in comparison to insulin treatment only (Fig. 5). This confirms potent intracellular activity of **13** and **14**.



Figure 5. Effect of **1**, **13** and **14** on % insulin-stimulated glucose uptake in 3T3-L1 adipocytes. Basal levels (B) with or without compound contain no insulin (I). I (with and without compound) administered at final concentration 100 nM. Results are mean and SEM relative to I only (n = 3 for **1** and n = 5 for **13** and **14**). I + 100 nM 13 vs. I p = 0.02; I + 1.0μ M **13** vs. I p = 0.02; I + 100 nM **14** vs. I p = 0.07; I + 1.0μ M **14** vs. I p = 0.01; B vs. B + **13** p = 0.98; B vs. B + **14** p = 0.94; B vs. B + **1** p = 0.21.

CONCLUSION

In this paper, we disclose the design, synthesis and evaluation of two new highly potent and isoform-selective TNKS inhibitors, 13 and 14. Crystal structures of these compounds bound into the catalytic domain of TNKS2 confirmed that, as designed, the quinazolin-4-one moiety occupied the nicotinamidebinding site, setting up the linker so that the quinoline moiety interacts with the adenosine-binding region. This dual-site design has led to the most potent and isoform-selective inhibitors reported to date, with $IC_{50} = 100 \text{ pM}$ for inhibition of TNKS2 by **14** and 1.2×10^5 -fold selectivity for inhibition of TNKS2 vs. the major PARP isoform, PARP1. Cellular uptake of these agents was demonstrated by their potent inhibition of Wnt / β catenin signaling in the low nM range. Significant anti-proliferative activity was demonstrated in DLD-1 human colon carcinoma cells at 100 nM under normal serum conditions. For the first time, truly potent and selective TNKS inhibitors are shown to increase insulin-stimulated glucose uptake, whereas previous studies have used non-selective pan-PARP inhibitors;¹³ this provides further evidence of a role of TNKSs in insulin-stimulated glucose transport and further studies will elucidate the mechanisms of this activation, presumably through the axinTNKS-KIF3A complex.¹² In comparative studies *in vitro*, the widely-used TNKS inhibitor **1** has been shown to be markedly less potent than **13** and **14** and to lack the exquisite isoform-selectivity of these new agents. The improved potency and isoform-selectivity of **13** and **14** is manifest in three comparative cellular functional assays, where they show useful activity in situations where **1** lacks potency or activity.

Compounds **13** and **14** are now available as potent and isoformselective TNKS inhibitors which inhibit the Wnt response pharmacologically in cells. They will have applications as molecular tools in studies on Wnt and related systems. These results also indicate that inhibition of TNKSs can increase sensitivity of cells to insulin, with potential application in Type-2 diabetes, as high doses of insulin can cause dysregulation of various signaling cascades (PI3K / Akt / mTOR).³⁰ Antiproliferative activity has also been demonstrated in human colon cancer cells under normal serum conditions, supporting TNKS as a therapeutic target in the many cancers with aberrant Wnt signaling. A new structural scaffold (**11**, **12**) for selective inhibitors of PARP2 has also been identified.

EXPERIMENTAL SECTION

Chemistry

The purity of target compounds were >95% as determined by ¹H and ¹³C NMR, high resolution mass spectrometry using electrospray ionization and HPLC analysis at two different wavelengths (see supplementary information for general experimental, spectra of all compounds and synthetic procedures of intermediate compounds).

Synthesis of target compounds 13 and 14.

2-(3-Oxo-3-(4-((quinolin-8-yl)aminocarbonyl)phenyla-

mino)propyl)quinazolin-4-one (13). Compound 6 (548 mg, 2.08 mmol) in dry DMF (50 mL) was treated with Pri₂NEt (2.96 g, 22.9 mmol), then carbonyldiimidazole (371 mg, 2.29 mmol), followed by addition of 11 (500 mg, 2.29 mmol). The mixture was stirred for 72 h under Ar. The solvent was evaporated and the residue was dissolved in EtOAc/MeOH (1:2, 70 mL). The organic solution was washed with water $(3 \times 30 \text{ mL})$ and brine $(3 \times 30 \text{ mL})$, then dried. Evaporation and chromatography (1:9) EtOAc / CH₂Cl₂ \rightarrow 1:9 MeOH / EtOAc) gave a mixture containing 13. Further chromatography (EtOAc) gave 13 (74 mg, 8%) as a pale purple solid: mp 265-268°C ¹H NMR ((CD₃)₂SO) δ 2.95-2.98 (4 H, m), 7.47 (1 H, t, J = 7.0 Hz), 7.63 (1 H, d, J = 8.0 Hz), 7.64-7.69 (2 H, m), 7.72-7.83 (2 H, m), 7.82 (2 H, d, J = 8.5 Hz), 8.00 (2 H, d, J = 8.5 Hz), 8.08 (1 H, d, J = 8.0 Hz), 8.46 (1 H, dd, J = 8.0, 1.5 Hz), 8.72 (1 H, d, J = 7.5 Hz), 8.97 (1 H, dd, J = 4.0, 1.5 Hz), 10.45 (1 H, s), 10.59 (1 H, s), 12.27 (1 H, s); ¹³C NMR ((CD₃)₂SO) δ 29.09, 32.34, 116.44, 118.70, 120.93, 122.13, 122.38, 125.77, 126.04, 126.76, 127.11, 127.86, 128.12, 128.44, 134.16, 134.35, 136.81, 138.26, 142.76, 148.74, 149.18, 156.52, 161.64, 163.96, 170.73; MS m/z 464.1722 [M + H]⁺ (C₂₇H₂₂N₅O₃ requires 464.1723).

8-Methyl-2-(3-oxo-3-(4-((quinolin-8-yl)aminocarbonyl)phenylamino)propyl)quinazolin-4-one (14). Compound **6** (514 mg, 1.95 mmol) in dry DMF (50 mL) was treated with $Pr^{i}_{2}NEt$ (2.78 g, 21.5 mmol), then carbonyldiimidazole (348 mg, 2.15 mmol), followed by addition of **12** (500 mg, 2.15 mmol). The mixture was stirred for 72 h under Ar. The solvent was evaporated and the residue was dissolved in EtOAc/MeOH (1:2, 70 mL). The solution was washed with water (3 × 30 mL) and brine (3 × 30 mL), then dried. Evaporation and chromatography (1:9 EtOAc / CH₂Cl₂ \rightarrow EtOAc) gave **14** (119 mg, 21%) as a beige solid: mp 280-282°C; ¹H NMR ((CD₃)₂SO) δ 2.44 (3H, s), 2.93

 $\begin{array}{l} (2 \text{ H, t}, J = 6.0 \text{ Hz}), 3.01 (2 \text{ H, t}, J = 7.0 \text{ Hz}), 7.31 (1 \text{ H, t}, J = 7.5 \text{ Hz}), 7.58 (1 \text{ H, m}), 7.63-7.69 (2 \text{ H, m}), 7.70 (1 \text{ H, dd}, J = 8.5, 1.0 \text{ Hz}), 7.83 (2 \text{ H, d}, J = 8.5 \text{ Hz}), 7.91 (1 \text{ H, dd}, J = 8.0, 1.0 \text{ Hz}), 8.00 (2 \text{ H, d}, J = 8.5 \text{ Hz}), 8.46 (1 \text{ H, dd}, J = 8.5, 2.0 \text{ Hz}), 8.72 (1 \text{ H, dd}, J = 7.5, 1.5 \text{ Hz}), 8.97 (1 \text{ H, dd}, J = 4.5, 2.0 \text{ Hz}), 10.76 (1 \text{ H, s}), 10.59 (1 \text{ H, s}), 12.25 (1 \text{ H, s}); 1^{3}\text{C NMR} \\ ((\text{CD}_{3)2}\text{SO}) \quad \delta 17.06, 28.99, 32.08, 116.45, 118.67, 120.76, 122.11, 122.38, 123.36, 125.44, 127.11, 127.86, 128.09, 128.34, 134.17, 134.59, 134.84, 136.81, 138.26, 142.91, 147.07, 149.17, 155.12, 161.94, 163.98, 170.98; \text{ MS } m/z \\ 478.1876 \left[\text{M} + \text{H}\right]^+ (\text{C}_{28}\text{H}_{24}\text{N}_{5}\text{O}_{3}\text{ requires 478.1879}). \end{array}$

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Counter-screening against PARP3, PARP4, PARP10, PARP12, PARP14, PARP15 and PARP16. Compounds **13** and **14** were counter-screened for inhibition of these isoforms using methods described previously.^{31, 32} The new inhibitors show no structural alerts for PAINS and are colorless and nonfluorescent.

Insulin-stimulated glucose uptake. 3T3-L1 fibroblasts (from the American Type Culture Collection), were cultured in DMEM and differentiated to adipocytes by treatment with insulin, dexamethasone and isobutylmethylxanthine, as described previously.²⁹ On the day of the experiment, 10-12 d post-differentiation, the cells were incubated with serum-free DMEM for 2 h at 37°C. Cells in the treatment group were treated with increasing concentrations of 13 or 14 for 1 h. At the end of the incubation period, the cells were washed thrice with Krebs-Ringer-HEPES (KRH) buffer (140 mM NaCl, 4.7 mM KCl, 2.5 mM CaCl₂, 1.25 mM MgSO₄, 2.5 mM NaH₂PO₄, 10 mM HEPES, (pH 7.4)) and incubated for 30 min with 13 or 14 and in either the absence or presence of insulin (100 nM) at 37°C. After the 30 min incubation period, 2-deoxy-D-[2,6-³H]glucose (final concentration 50 μ M, 0.1 μ Ci well⁻¹) was added for 5 min and the cells were washed four times with ice-cold KRH buffer. Nonspecific uptake of 2-deoxy-D-glucose was measured in the presence of 10 µM cytochalasin B. The cells were lysed in aq. NaOH (0.1 M) and radioactivity was counted in a TriCarb Packard scintillation counter (Perkin-Elmer). The concentrations of proteins were measured using BCA protein assay kit (Thermo Fisher Scientific). Results were calculated as nmol of 2-deoxy-D-glucose min⁻¹ (mg protein)⁻¹ and are expressed as % of insulin-only control. Statistical analysis; results were analyzed using two-tailed paired t tests.

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Author Contributions

The manuscript was written through contributions of all authors. The authors declare no competing financial interest.

Accession codes

Coordinates and structure factors are deposited at the Protein Data Bank with codes 5FPF and 5FPG. Authors will release the atomic coordinates and experimental data upon article publication.

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ABBREVIATIONS

NAD⁺, Nicotinamide Adenosine Dinucleotide; ADP, Adenosine diphosphate; GLUT4, Glucose Transporter Type-4; CDI, N,N'-Carbonyldiimidazole; IC₅₀, half-maximal inhibitory concentration; PDB, Protein Data Bank; TCF, T-cell factor; LEF, Lymphoid Enhancer-binding Factor; DMEM, Dulbecco's Modified Eagle Medium; BCA, Bicinchoninic acid.

ASSOCIATED CONTENT

Supporting Information. Synthetic details, ¹H NMR, ¹³C NMR, HRMS, HPLC, TNKS1 enzyme assay method, TNKS1 IC₅₀ graphs, TNKS2 enzyme assay method, TNKS2 IC₅₀ graphs, PARP1 enzyme assay method, PARP1 IC₅₀ graphs, PARP2 enzyme assay method, PARP2 IC₅₀ graphs, Wnt signaling inhibition cellular assay method, Wnt signaling inhibition IC₅₀ graphs, X-ray crystallography refinement data, colony-forming cellular assays experimental and Molecular Formula Strings. This material is available free of charge via the Internet at http://pubs.acs.org.

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