

RESEARCH ARTICLE

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Identification of molecular glues of the SLP76/14-3-3 protein–protein interaction†

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The stabilisation of protein–protein interactions (PPIs) through molecular glues is a novel and promising approach in drug discovery. In stark contrast to research in protein–protein inhibition the field of stabilisation remains underdeveloped with comparatively few examples of small-molecule stabilisers of PPIs reported to date. At the same time identifying molecular glues has received recent sustained interest, especially in the fields of targeted protein degradation and 14-3-3 PPIs. The hub-protein 14-3-3 has a broad interactome with more than 500 known protein partners which presents a great opportunity for therapeutic intervention. In this study we have developed an HTRF assay suitable for HTS of the 14-3-3/SLP76 PPI and have completed a proof of concept screen against a chemically diverse library of 20 K molecules. The adaptor protein SLP76 has been reported to interact with 14-3-3 proteins downstream of the TCR playing an important role in mediating its own proteasomal degradation. We believe that stabilisation of this PPI could be exploited to potentiate degradation of SLP76 and therefore inhibit TCR signalling. This would represent an interesting alternative to other approaches in the field of targeted protein degradation. Here we disclose 16 novel stabilisers of the 14-3-3/SLP76 PPI across multiple different chemotypes. Based on the early results presented here we would recommend this approach to find molecular glues with broad applicability in the field of 14-3-3 PPIs.

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Introduction

Inhibition of protein–protein interactions has become an established approach in drug discovery and has delivered successful examples to the market and in clinical trials.^{1–3} In contrast, the stabilisation of protein–protein interactions (PPI) remains a relatively novel field in drug discovery but has seen a considerable increase in interest over the last two decades. Although stabilising PPIs is considered a challenging approach, it has significant advantages. The binding epitopes generated at the interface of two different target surfaces confer an intrinsically higher potential for selectivity and theoretically even modest enhancements of the affinity of an already occurring PPI could lead to useful levels of activity.⁴

The natural immunosuppressant products cyclosporine and FK506 were among the first reported examples of molecular

glues, although their mechanism of action was elucidated retrospectively.^{5–7} Most recently, small-molecule approaches have been pursued. PROTACs (proteolysis targeting chimeras) are classes of bifunctional small molecules that promote proximity between an ubiquitin ligase and a substrate protein, leading to the degradation of the latter.^{8–11} Smaller, monovalent molecules grouped under the IMiDs drug class, capable of promoting the ubiquitination of substrates targeting them for degradation, have also been described with thalidomide and lenalidomide the main examples.^{12–15} The ability to target proteins for degradation using small molecules has expanded the range of accessible new targets previously considered to be undruggable.^{16,17}

So far, rationally designed small molecules aimed at the stabilisation of a PPI between an E3 ligase and its specific interaction partner has been the direct route to enhance protein degradation.^{18–21} However, mechanisms that indirectly promote protein degradation might be an alternate approach to find novel, therapeutically useful chemical matter.

Protein degradation can be modulated *via* ubiquitination,²² phosphorylation,^{23,24} acetylation,²⁵ sumoylation,²⁶ or, as some studies have suggested, *via* interaction with adaptor proteins such as 14-3-3.^{27–31} 14-3-3 proteins are a family of eukaryotic adaptor proteins that are known for recognizing specific pSer/pThr containing motifs

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14-3-3 has been reported to interact with the protein SLP76 *via* one specific phosphorylation site located on SLP76, Ser376.^{59,60} SLP76 is an adaptor protein that orchestrates the signalling downstream of TCRs helping to modulate the immune response.^{61,62} The SLP76 phosphorylation on Ser376 is performed by the kinase HPK1 (hematopoietic progenitor

In order to find stabilisers of the 14-3-3/SLP76 PPI we generated a protein system composed of full-length 14-3-3 γ and a 20 KDa phosphorylated SLP76 construct. This introduced a higher degree of complexity since 14-3-3 PPIs are more typically investigated using 12-mer synthetic peptides to mimic the 14-3-3 binding partner. We then developed and ran an HTRF-HTS (homogeneous time resolved fluorescence high throughput screening) on the UCB “Diversity Set” of 20 000 small molecules. The “Diversity Set” is a subset of the larger UCB HTS compound collection specifically selected for lead-like molecular properties and chemical diversity. We also used an unrelated PPI that shared the same FRET pair as the 14-3-3 γ /SLP76 system as a counterscreen, which allowed us to identify specific potential stabilisers of this interaction. The hits found were further characterised performing HTRF dose-response and dose-ratio assays and the stabilisation effect orthogonally confirmed by SPR.

The 14-3-3 γ /SLP76 PPI and HTRF assay set up description

The HTRF assay was set up by labelling 14-3-3 γ and SLP76 with a matched pair of fluorophores. 14-3-3 γ was labelled with Tb, generating the donor molecule, and SLP76 with AF647, generating the acceptor molecule. The read-out in HTRF originates by the proximity of the two proteins resulting in a FRET signal, which is directly proportional to the amount and strength of the interacting proteins (Fig. 2a).

The performance of the initial single point screening of the 20 000 molecule UCB Diversity Deck against the 14-3-3y/

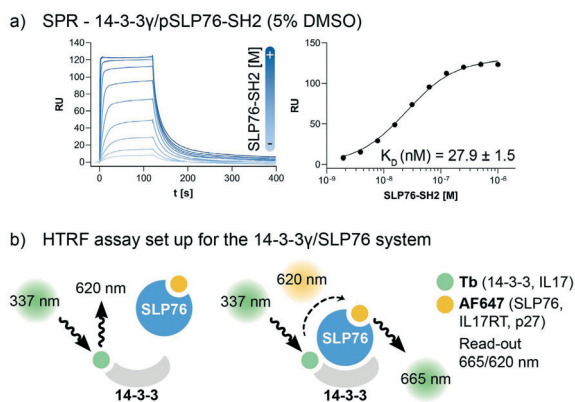


Fig. 1 Assay set-up for the 14-3-3 γ /SLP76 PPI. a) SPR binding assay of the SLP76-SH2 construct binding to 14-3-3 γ in the presence of 5% DMSO. The K_D value has been extrapolated from the binding curve reported on the right of the sensorgrams. b) HTRF assay set-up. The two proteins of interest, SLP76 and 14-3-3 γ have been labelled with Tb and AF647, respectively, to generate a suitable matched pair of donor molecule (Tb) and acceptor molecule (AF647). The donor molecule, Tb labelled 14-3-3, is excited at the proper wavelength of 337 nm. When the acceptor is not in the proximity (no binding) no signal is detected. When SLP76 bound to 14-3-3 brings the acceptor molecule AF647 close to the donor, energy transfer occurs between the fluorophores pair. A radiation with the wavelength of 665 nm is consequently emitted to generate a read-out (665/620 nm). All HTRF protein systems used in this work are reported in the legend.

SLP76 PPI system is shown in (Fig. 2a). The peptide R18 is a well characterised inhibitor of 14-3-3 PPIs^{64,65} and was therefore chosen as the assay negative control and was also an important reagent used during assay validation. Unfortunately, there are no reported stabilisers of 14-3-3/SLP76 interactions and therefore no true positive controls. Of course, the fundamental aim of this work was to discover molecular glues of this interaction which can then be used as starting points and tool compounds to evaluate the therapeutic potential of stabilising the complex. The cut-off for selection of hits in the first round of screening was set at 20% stabilisation (or -20% inhibition) at a concentration of 100 μ M with the reference control set at

100% inhibition and all the screening outcomes normalised accordingly (Fig. 2b).

The cut-off expressed in number of standard deviations of the DMSO control from the mean was $4 \times SD_{DMSO}$ (or $30 \times SD_{DMSO}$ calculated using raw data). The cut-off chosen from the primary screen left us with 1136 hits, roughly 5% of the initial 20 000 molecules. Of these 1136 small molecules, 660 repeated in a confirmatory screen with the same cut-off threshold; roughly 3% of the initial 20 000 compounds. These 660 hits were subsequently tested in an assay using IL17/receptor as an unrelated PPI which shared the same FRET acceptor/donor pair as the 14-3-3 γ /SLP76 system (Fig. 3a).

The matched FRET pair counter screen was specifically introduced to reduce the number of false positive hits and to focus on molecules that selectively stabilised the 14-3-3 γ /SLP76 system. Using this counter screen, we were able to further refine compounds of most interest to 428 hits as summarised in Fig. 3b.

The hits selected in this way were then ranked according to their inhibition ratio (% inhibition SLP76/% inhibition IL17), with the most selective compounds (highest ratios) prioritised for further study. This allowed us to further focus our efforts on a shortlist of 64 compounds which demonstrated little to no stabilisation of the counter-screen system with the results of this triage process summarised in Fig. 4a.

HTRF dose-response assay on the selected 64 compounds

The compounds which appeared selective in the single point screening were tested as dose responses on 14-3-3 γ /SLP76 (Fig. 4b). Of the 64 tested in dose response, 30 did not show any dose-response effect. Of the remaining 34 compounds, 16 were selected as the most promising hits to follow up based on EC₅₀ values (Table 1). All 16 compounds demonstrated a concentration dependent increase in HTRF signal as a result of the binding of the molecules to the 14-3-3/SLP76 complex. EC₅₀ values estimated from the fitting curves were between 2.2 and 110 μ M (Fig. 4b). These 16 compounds were retested in dose response using 10 mM

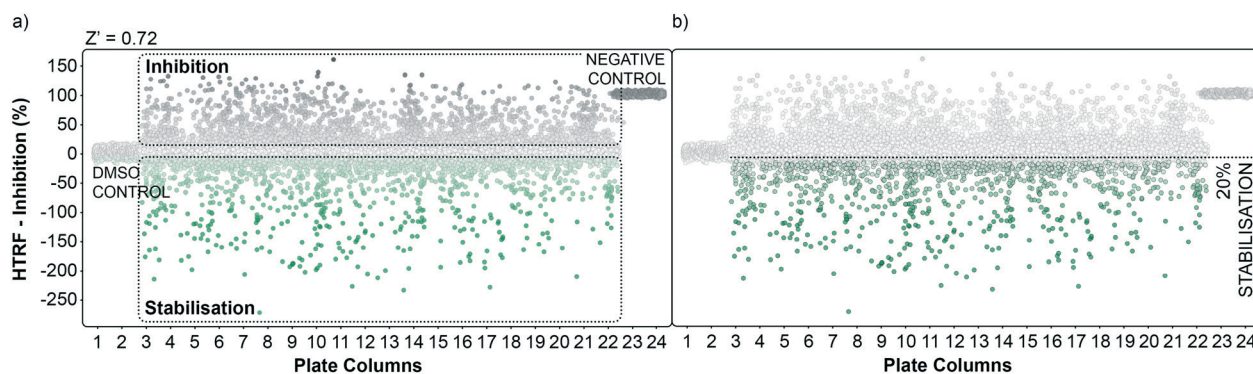


Fig. 2 Graphical representation of the high throughput screening performance. a) Dots representation of the HTS in the plate format. Potential inhibitors are represented as grey dots, potential stabilisers are represented as green dots. DMSO control and negative control are grouped in plate columns 1, 2 and 23, 24 respectively. The calculated overall Z' factor for the assay was 0.72. b) An initial cut-off of 20% stabilisation was used to select hits to follow-up.

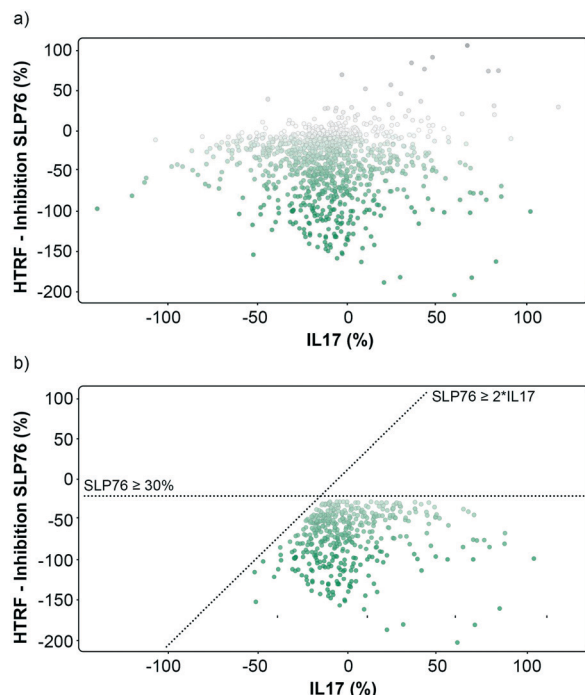


Fig. 3 Graphical representation of the repeated 1136 hits tested on 14-3-3/SLP76 and PPI X. a) Representation of the hits expressed as percent inhibition against 14-3-3 γ /SLP76 and IL17/IL17R. Potential 14-3-3/SLP76 stabilisers are represented as green dots. b) Selection conditions applied to the hits were to retain compounds that showed an effect on SLP76 $\geq$ -30% and simultaneously at least a two-fold greater stabilisation than IL17 PPI, SLP76 $\geq$ 2*IL17.

DSMO stock solutions freshly prepared from solid and pleasingly they were all confirmed as stabilisers of the 14-3-3 γ /SLP76 PPI system (Fig. 5c). To test whether the

concentration-dependent effect would influence other PPI systems as well, the compounds were also tested on IL17/IL17R as an unrelated PPI (Fig. 5a) and on the 14-3-3 ζ /p27 system (Fig. 5b) as an example of another 14-3-3 PPI. In all cases the same FRET pair was used to label the different protein systems.

None of the 16 compounds showed an effect on IL17/IL17R, as expected from the primary counter screen assay. However, eight compounds showed a dose-response effect on the 14-3-3 ζ /p27 system that exceeded the normalised response of 1.5, with 2.0 being the theoretical maximal response. This evidence indicates that these compounds are not specifically selective for the 14-3-3 γ /SLP76 PPI and provides an opportunity for further exploration. Although the key objective of this study was to find selective stabilisers of the 14-3-3 γ /SLP76 interaction, the prospect of finding generic 14-3-3 PPI stabilisers would be of general benefit to research in this area. Furthermore, if the binding site of these compounds could be characterised it would open the possibility to rationally build in selectivity for different 14-3-3 protein-protein interactions through structure-based drug design.

Orthogonal SPR confirmation on the selected 16 compounds

Of the 16 hit compounds 13 were tested in an orthogonal SPR assay in which each compound was flowed with SLP76 over 14-3-3 γ immobilised on the chip. Runs at different concentrations of compound were compared to the runs in absence of compound. Of the 13 compounds tested this way, 8 showed a difference in off-rate indicative of increased binding of SLP76 to 14-3-3 γ and were subsequently tested at multiple concentrations to establish a concentration-dependent effect (Fig. S2–S17 †). All 8 compounds proved to

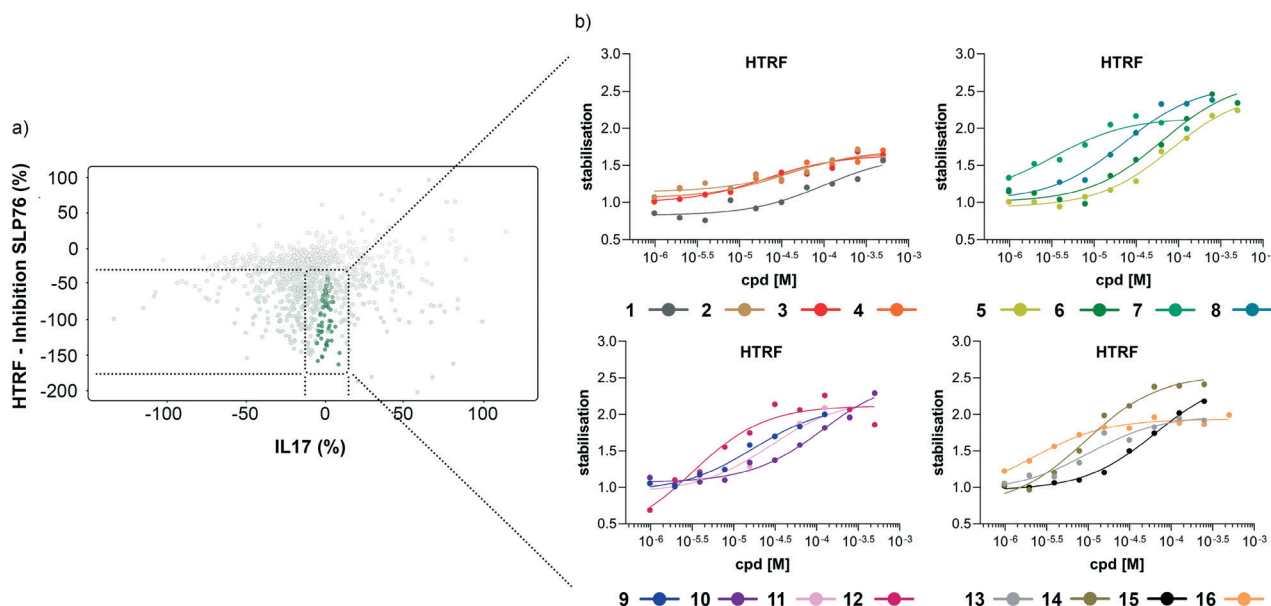


Fig. 4 Representation of the 64 small molecules selected on the basis of SLP76 stabilisation and IL17/IL17R counter-screen and 14-3-3 γ /SLP76 dose response curves for the best 16 compounds. a) Selection of 64 small molecules represented as green dots within dotted lines. b) Dose response curves of the best 16 out of the 64 compounds tested. Estimated EC50 values for every compound are reported in (Table 1).

Table 1 Summary table of the 16 compounds identified from the HTRF dose-response assay

Molecule	HTRF EC ₅₀ (μM)		HTRF K _D improvement	SPR RU (%) mass increase
	14-3-3γ/SLP76		14-3-3γ/SLP76	14-3-3γ/SLP76
	14-3-3γ/SLP76	14-3-3ζ/p27	14-3-3γ/SLP76	14-3-3γ/SLP76
1	19.1 ± 7.7	IA ^a	3.3× ^c	66.4
2	18.6 ± 5.5	IA ^a	4.1× ^c	67.6
3	14.4 ± 1.9	IA ^a	10× ^c	66.9
4	17.4 ± 4.9	IA ^a	3.4× ^c	57.1
5	71.1 ± 23.9	IA ^a	4.7× ^c	Ns ^d
6	33.5 ± 10.7	IA ^a	Nm ^b	Ns ^d
7	5.3 ± 1.9	IA ^a	4.4× ^c	57.7
8	69.1 ± 22.6	53.9 ± 17.1	3.5× ^c	61.2
9	24.5 ± 5.8	5.8 ± 2.2	11× ^c	58.7
10	70.1 ± 8.7	16.5 ± 10.6	1.4× ^c	Ns ^d
11	29.7 ± 21.8	128.9 ± 70.5	Nm ^b	Nm ^b
12	3.8 ± 1.2	0.43 ± 0.37	5.2× ^c	67.4
13	4.9 ± 1.1	IA ^a	1.1× ^c	Ns ^d
14	21.2 ± 11.3	12.6 ± 14.4	14.6× ^c	Ns ^d
15	17.1 ± 5.2	11.6 ± 6.1	Nm ^b	Nm ^b
16	1.2 ± 0.7	80.6 ± 53.4	1.8× ^c	Nm ^b

^a IA: inactive no stabilisation observed in dose-response. ^b Nm: not measured. ^c *n*-Fold 14-3-3γ/SLP76 K_D improved in presence of increasing concentration of small molecule. ^d Ns: no stabilisation observed in SPR.

be dose responsive leading to a concentration-dependent increase in mass on the chip. The effect of the compounds

on 14-3-3γ/SLP76 was measured by calculating the percentage of SLP76 remained on the chip after the dissociation phase and immediately before: RU (%) = RU 5 s before dissociation/RU +240 s after dissociation. Dose-response curves were extrapolated from those sensorgrams plotting the RU (%) mass increase over the increase in compound concentrations.

Analysis of hit compounds

The structures of all 16 hits and data from all assays used to triage the compounds are summarised in Table 1. Of the 16 compounds tested by HTRF in dose response, compounds **1**, **2**, **3**, **4**, **7**, **8**, **9**, **12** were orthogonally confirmed by SPR and of those, compounds **1**, **2**, **3**, **4**, **8** were selective for 14-3-3γ/SLP76 over 14-3-3ζ/p27 (Fig. S2–S5, S8–S10 and S13†). Ten of the sixteen hit compounds could be grouped into four structurally distinct chemotypes with the remaining 6 compounds singleton hits.

Compounds **1** and **2** belong to an interesting benzo-fused tricyclic oxazolidinone system. Both compounds were selective for the 14-3-3γ/SLP76 interaction with similar activities and no observed stabilisation in the 14-3-3ζ/p27

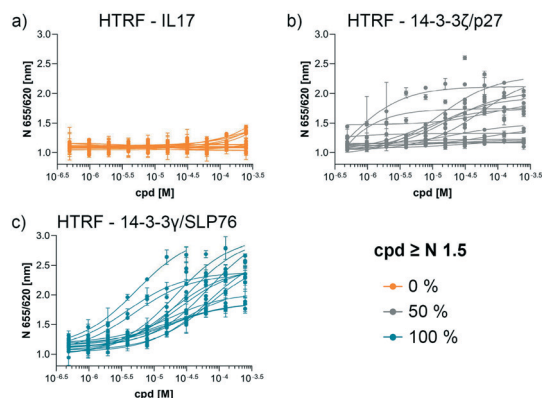


Fig. 5 Comparison of the dose response assay of the 16 compounds on the systems IL17/IL17R, 14-3-3ζ/p27 and 14-3-3γ/SLP76. a) Dose response of the 16 compounds on IL17/IL17R. None of the compounds showed an effect on IL17/IL17R. b) Dose response of the 16 compounds on 14-3-3ζ/p27. 8 out 16 compounds showed an effect greater than 1.5 normalised response. c) All 16 compounds repeated on 14-3-3γ/SLP76.



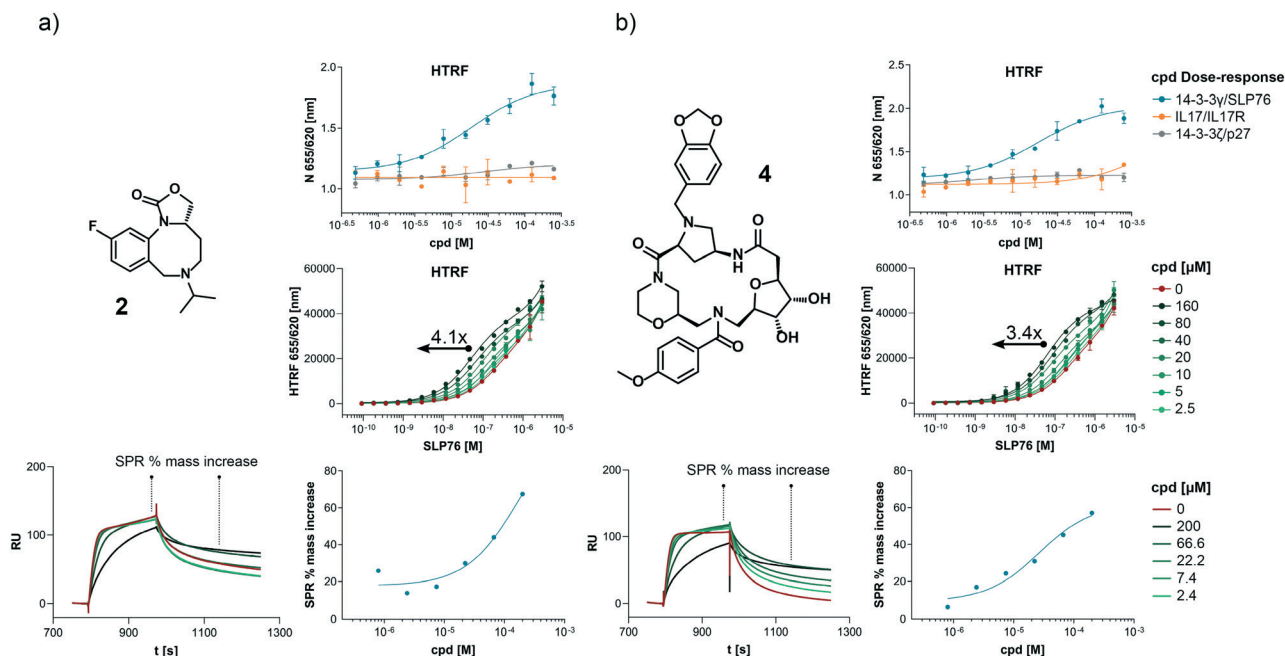


Fig. 6 Combined set of assays example for the compound 2 and 4. a) HTRF dose response comparison of the three systems used. HTRF dose ratio assay on the 14-3-3γ/SLP76-SH2 system. The arrow represents the increment in potency upon increasing compound concentration. Sensorgrams generated by SLP76-SH2 flowing over 14-3-3γ in absence (as reference) and in the presence of different concentration of compounds. The plot of the reference points taken from the sensorgram used to extrapolate the SPR apparent EC50 is reported to the right. The reference points before and after the dissociation phase are highlighted in the sensorgrams (bottom left). b) The same set of assays are repeated on compound 4.

HTRF assay. The stabilising effect of these compounds was orthogonally confirmed and equipotent by SPR (Fig. 6a). These oxazolidinones have good lead-like properties with low MW, PSA and good $A \log P$ (SI) which makes them excellent candidates for hit expansion. The presence of a chiral centre offers the prospect to investigate if there is an enantiomeric preference in stabilisation.

An equally interesting chemotype are the 16-membered macrocyclic compounds 3 and 4 which were also shown to be selective for the 14-3-3γ/SLP76 system as well as being orthogonally confirmed in the SPR assay (Fig. 6b). Although the macrocycles show very similar levels of activity in the 14-3-3γ/SLP76 HTRF assay to compounds 1 and 2, they both appear to perform better in the SPR stabilisation assay with compound 3 showing one of the strongest effects in K_D improvement (10 fold) in the SLP76 HTRF assay across all compounds tested. The macrocycles lie outside the range of conventional lead-like properties with MW of 609 and 652 respectively, highly polarity ($A \log P$ -1.3 and -0.5) and with PSA around 150 which could impact cell permeability. However, this should not preclude a more detailed investigation and indeed these compounds could give valuable insight as tools for future structural studies.

The third group of hits, compounds 5 and 6, are characterised by having a quaternary positively charged amine group. Both showed activity in the 14-3-3γ/SLP76 HTRF assay although with modest EC50s and were selective over 14-3-3ζ/p27. However, neither of these two compounds were

confirmed in SPR with no observable stabilisation effect (Fig. S6 and S7†).

The fourth group of compounds: 7, 8, 9 and 10 all share a triazolothiadiazole heteroaromatic scaffold or in the case of compound 10 the closely related triazolothiadiazine structure. This set of compounds is especially attractive in that they have low MW with good molecular properties in fragment space and have significant potential for further exploration. It is also notable that these compounds form the largest structurally related cluster of SLP76 stabilisers from the UCB Diversity Deck. Compound 7 is the stand-out hit as a selective 14-3-3γ/SLP76 stabiliser with EC50 of 5.3 μM, a fourfold increase in K_D and no measurable modulation of the 14-3-3ζ/p27 system. Compound 7 also has a strong concentration dependence in off-rate in SPR when compared to other compounds in this group (e.g. compound 10 demonstrates no observable stabilisation in the SPR assay). With a MW of only 203 compound 7 demonstrates remarkable modulation of the 14-3-3γ/SLP76 system and is a priority for further focussed hit expansion. What is even more interesting is that the closely related analogues in this group are also able to stabilise the 14-3-3ζ/p27 PPI to a lesser or greater extent. This opens up the intriguing possibility that these compounds could be generic modulators of 14-3-3 protein-protein interactions, with the potential to tune-in selectivity for a specific protein pair. This speculation would of course require a larger confirmatory study to expand both the chemical matter around these scaffolds and the numbers



cryptate and AF647 were added to 14-3-3 γ and SLP76 respectively. The mixtures were left in the dark for 1 h at room temperature. After labelling, the buffers were ultimately exchanged to assay buffer (50 mM Tris pH 7.5, 150 mM NaCl, 5 mM MgCl₂, 0.05% v/v Tween-20). All the buffer exchange steps were performed with Zeba™ Spin Desalting Columns, 7 K MWCO, 0.5 mL (ThermoFisher) and P-10 Desalting Columns (Cytiva) for higher volumes.

Homogeneous time-resolved fluorescence assay development and high throughput screening

384-Well logistic plates were pre-filled with 2 μ L of compounds at 2 mM, 100% DMSO, except for columns 1, 2, 23 and 24. Columns 1, 2 were filled with 2 μ L of DMSO while columns 23, 24 were filled with 2 μ L of the 14-3-3 inhibitor R18 at 20 μ M using a Multidrop Dispenser (ThermoScientific). Next, 40 μ L of protein mixture containing Tb-labelled 14-3-3 γ at 1 nM and AF647 labelled SLP76 at 600 nM in assay buffer (50 mM Tris pH 7.5, 150 mM NaCl, 5 mM MgCl₂, 0.05% v/v Tween-20) were added using a Multidrop Dispenser (ThermoScientific). Hence, the final assay concentrations were 14-3-3 γ -Tb at 1 nM, SLP76-AF647 at 600 nM, compounds at 100 μ M, R18 at 1 μ M, and DMSO at 5% v/v. To perform the assay, 30 μ L volumes were then transferred using a Biomek FX^P Automated Workstation (Beckman Coulter) into Corning 384-well 3574 assay plates. The plates were incubated at room temperature with gentle shaking for 4 h. Finally, the data were collected on a PHERAstar FSX plate reader (BMG Labtech) with an λ_{ex} 337 nm, λ_{em} 665 nm and 620 nm HTRF filter setting. The data were exported in IDBS ActivityBase (IDBS) where they were normalised setting the R18 negative control as 100% inhibition and the DMSO control as 0%. Negative percentage values were therefore associated with a stabilisation of the 14-3-3 γ /SLP76 interaction. The threshold of -20% inhibition (or 20% stabilisation) was chosen to select the hits to follow up. The selected hits were retested on 14-3-3 γ /SLP76 and were also tested against an unrelated protein pair (IL-17/receptor) in a similar assay setup. Only the ones that had an effect on 14-3-3 γ /SLP76 and not on the IL-17/IL17 receptor system were selected. All the assays were performed as described above.

Protein expression and purification

Homogeneous time-resolved fluorescence dose-response and dose-ratio

384 logistic plates were pre-filled with 40 μ L of compounds at 10 mM, 100% DMSO in column 3. Columns 1, 2 and 4 to 22 were filled with 20 μ L of 100% DMSO with a Multidrop Dispenser (ThermoScientific). 2-Fold dilutions of the compounds were carried over from column 3 to 22, with a CyBio Felix liquid handler (analytikjena). 2 μ L of R18 peptide at 20 μ M was added to columns 23 and 24 of the Corning 384-well 3574 final assay plates with a Multidrop Dispenser (ThermoScientific). 40 μ L of protein mixture, containing Tb labelled 14-3-3 γ at 1 nM and AF647 labelled SLP76 at 600 nM in assay buffer (50 mM Tris pH 7.5, 150 mM NaCl, 5 mM MgCl₂,

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Surface Plasmon resonance

To the best of our knowledge this is the first report in the field of 14-3-3 PPIs to use a phosphorylated protein construct in an HTS HTRF format. In our opinion, such protein constructs have greater relevance than the short synthetic phosphopeptides that have been extensively used to represent the client protein in the 14-3-3 field to date. Although these phosphopeptides remain valuable tools to enable rapid early investigation of new 14-3-3 PPIs, they have inherent limitations as screening systems to find modulators of these interactions. By contrast working with full-length/truncated versions of phosphorylated 14-3-3 binding partners substantially extends the opportunity to discover druggable binding sites beyond the 14-3-3 amphipathic binding pocket. In this regard we believe that the results in this study support

wider use as an approach to find molecular glues of 14-3-3 protein-protein interactions. Of course, the novel 14-3-3 stabilisers we report in this paper remain early hits and should still be treated cautiously. There is a need to continue to characterise these compounds to understand where they bind and how they stabilise the 14-3-3 ternary complex. Our priority will be to use X-ray crystallography and NMR to locate and rationalise the binding of the small molecules identified here. This will open the path for future optimisation of these molecules to tune and increase their stabilisation effect and ultimately demonstrate a therapeutically useful function.

Author contributions

CO, JD and SL conceptualised and supervised the project. MR performed formal analysis and developed the HTRF methodology. MW developed the SPR methodology. LS conducted the investigation and visualisation process and wrote the original draft. CO, JD, SL, MR, MW and LS reviewed and edited the manuscript. CO is co-founder of Ambagon Therapeutics.

Conflicts of interest

There is no conflict of interest to declare.

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