RESEARCH ARTICLE

REVISED The dipeptidyl peptidase IV inhibitors vildagliptin and K-579 inhibit a phospholipase C: a case of promiscuous scaffolds in proteins [version 3; peer review: 2 approved]

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V3 First published: 27 Dec 2013, 2:286
<https://doi.org/10.12688/f1000research.2-286.v1>
 Second version: 14 Jan 2015, 2:286
<https://doi.org/10.12688/f1000research.2-286.v2>
 Latest published: 29 Jan 2015, 2:286
<https://doi.org/10.12688/f1000research.2-286.v3>

Abstract

The long term side effects of any newly introduced drug is a subject of intense research, and often raging controversies. One such example is the dipeptidyl peptidase-IV (DPP4) inhibitor used for treating type 2 diabetes, which is inconclusively implicated in increased susceptibility to acute pancreatitis. Previously, based on a computational analysis of the spatial and electrostatic properties of active site residues, we have demonstrated that phosphoinositide-specific phospholipase C (PI-PLC) from *Bacillus cereus* is a prolyl peptidase using *in vivo* experiments. In the current work, we first report the inhibition of the native activity of PI-PLC by two DPP4 inhibitors - vildagliptin (LAF-237) and K-579. While vildagliptin inhibited PI-PLC at micromolar concentrations, K-579 was a potent inhibitor even at nanomolar concentrations. Subsequently, we queried a comprehensive, non-redundant set of 5000 human proteins (50% similarity cutoff) with known structures using serine protease (SPASE) motifs derived from trypsin and DPP4. A pancreatic lipase and a gastric lipase are among the proteins that are identified as proteins having promiscuous SPASE scaffolds that could interact with DPP4 inhibitors. The presence of such scaffolds in human lipases is expected since they share the same catalytic mechanism with PI-

Open Peer Review

Approval Status

	1	2
version 3 (revision) 29 Jan 2015		
version 2 (revision) 14 Jan 2015		view
version 1 27 Dec 2013	view	view

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- Mark D Gorrell**, Centenary Institute, Newtown, NSW, Australia

Any reports and responses or comments on the

PLC. However our methodology also detects other proteins, often with a completely different enzymatic mechanism, that have significantly congruent domains with the SPASE motifs. The reported elevated levels of serum lipase, although contested, could be rationalized by inhibition of lipases reported here. In an effort to further our understanding of the spatial and electrostatic basis of DPP4 inhibitors, we have also done a comprehensive analysis of all 76 known DPP4 structures liganded to inhibitors till date. Also, the methodology presented here can be easily adopted for other drugs, and provide the first line of filtering in the identification of pathways that might be inadvertently affected due to promiscuous scaffolds in proteins.

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article can be found at the end of the article.

Keywords

diabetes , Bacillus cereus , PI-PLC , serine protease , lipase

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Competing interests: No competing interests were disclosed.

Grant information: FMG thanks the Spanish Ministerio de Ciencia e Innovacion for grant No. BFU 2012-36241, and the University of the Basque Country for grant No. IT 849-13. BJ and RV acknowledge financial support from Tata Institute of Fundamental Research (Department of Atomic Energy). Additionally, BJR is thankful to the Department of Science and Technology for the JC Bose Award Grant. BA extends gratitude to the University of Iceland Research Found for supporting the project financially. AMD wishes to acknowledge grant #12-0130-SA from California Department of Food and Agriculture CDFA PD/GWSS Board. MO was supported in part by a Grant-in-aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology, Japan; (grant No. 21790431). The work in Liege was supported by an IUAP program funded by the Belgian federal government.

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How to cite this article: Chakraborty S, Rendón-Ramírez A, Ásgeirsson B *et al.* **The dipeptidyl peptidase IV inhibitors vildagliptin and K-579 inhibit a phospholipase C: a case of promiscuous scaffolds in proteins** [version 3; peer review: 2 approved] F1000Research 2015, 2:286 <https://doi.org/10.12688/f1000research.2-286.v3>

First published: 27 Dec 2013, 2:286 <https://doi.org/10.12688/f1000research.2-286.v1>

REVISED Amendments from Version 2

In the current version, we have changed the title, and cited previous research (ref 41 and 54) based on referee suggestions.

We have also included some minor corrections as suggested by a co-author.

See referee reports

Introduction

Oral glucose elicits a greater insulin response than intravenous glucose infusion, a phenomenon known as the incretin effect¹. This effect is mostly attributed to the intestinally derived hormones glucagon-like peptide-1 (GLP-1) and gastric inhibitory polypeptide (GIP)². These hormones have a very short half-life as they are rapidly inactivated by the ubiquitous enzyme dipeptidyl peptidase-IV (DPP4)³. The finding that the incretin effect is impaired in subjects with type 2 diabetes⁴ led to two major types of GLP-1 based therapies⁵ - intravenously or sub-cutaneously administered GLP-1 mimetics that are resistant to DPP4 (exenatide, liraglutide, etc.)⁶, and the orally administered gliptins that prolong the physiological actions of incretin hormones by inhibiting DPP4 (sitagliptin, vildagliptin, etc.)⁷⁻⁹. Due to the multifarious roles played by the DPP4 enzyme¹⁰⁻¹², the possible side effects of these drugs (acute pancreatitis, pancreatic cancer, etc.¹³⁻¹⁵) are strongly contested by researchers who argue that current statistics are insufficient^{16,17} to conclusively attribute these side effects to the otherwise beneficial GLP-1 drugs¹⁸. Compound promiscuity is another phenomenon that might play a crucial role in determining the side effects of these therapies, although this aspect has rarely been pursued intensively¹⁹.

Previous work by our group has established the spatial and electrostatic congruence in cognate residue pairs of the active site in proteins with the same functionality (CLASP)^{20,21}. CLASP analysis indicated that the phosphoinositide-specific phospholipase C (PI-PLC) from *Bacillus cereus* has spatial and electrostatic congruence with a serine protease motif²². This was validated by protease assays, mass spectrometry and by inhibition of the native phospholipase activity of PI-PLC by the well-known serine protease inhibitor AEBSF ($IC_{50} = 0.018$ mM). The specificity of the protease activity was for a proline in the amino terminal, suggesting that PI-PLC is a prolyl peptidase, similar to the DPP4 enzyme. This finding led us to believe that the gliptins would have similar inhibitory effect on PI-PLC. In the current work, we have confirmed the inhibition of the native phospholipase activity of PI-PLC using two gliptins - vildagliptin²³ (at μ -molar concentrations) and K579²⁴ (at nano-molar concentrations).

Subsequently, we used a motif derived from a DPP4 protein²⁵, in addition to the trypsin motif used previously²², to query a comprehensive and non-redundant (50% sequence identity) list of ~5000 human proteins with known structures using CLASP, intending to identify other proteins that might be inhibited by the gliptins. From the set of proteins with significant congruent matches with these two motifs, we identified a pancreatic lipase²⁶ and a gastric lipase²⁷,

keeping the context of lipases, acute pancreatitis and GLP-1 based therapies in mind. Our findings rationalize the elevated levels of serum lipase found in patients undergoing DPP4 inhibitor based therapies^{28,29}, although these reports are in disagreement with other findings^{30,31}. While it is logical and expected to find scaffolds that are congruent to trypsin and DPP4 active sites in lipases based on the current results and our previous findings²², we also show the presence of the serine catalytic triad in close proximity to the active site residues of proteins which have a completely different enzymatic mechanism (for example, in glutaminyl cyclase which is a transferase³²). This corroborates the current belief that convergent evolution occurs more frequently than previously believed³³. Thus, we propose a rational method to identify proteins that might have unintended and undesirable interactions with newly introduced compounds, and substantiate our claims by demonstrating the inhibition of the native phospholipase activity of PI-PLC from *B. cereus* using gliptins that are used in type 2 diabetes therapy.

Results

The active site motifs

The active sites of serine proteases differ in their specificities owing to residues other than the conserved catalytic triad. Thus, in addition to the trypsin motif used previously (Asp102, Ser195 and His57 - PDBid 1A0J)²² (Motif1), we choose another motif from a DPP4 enzyme (Asp708, Ser630 and His740 - PDBid:1N1M) (Motif2) (Table 1). Apart from the catalytic triad, we chose another non-polar residue in order to increase the specificity of the matches (Ala56 in Motif1 and Val711 in Motif2). This fourth residue is chosen as the closest residue to any one of the catalytic triad residues. Using the ability of CLASP to include stereochemically equivalent residues, this last residue could be matched by another non-polar residue - one of Gly, Ala, Val, Leu, Ile or Met. Further, it has been seen that the second (ac) and fifth (bd) (Table 1) pairwise electrostatic potential differences (EPD) are not discriminatory - thus, this pair is not used to score the EPD difference (although it is included in the distance deviation score).

Inhibition of phosphoinositide-specific phospholipase C (PI-PLC) using dipeptidyl peptidase-IV (DPP4) inhibitors. DPP4 (EC 3.4.14.5), a serine protease that is expressed in many tissues (kidney, liver, lung, intestinal membranes, lymphocytes and endothelial cells), cleaves peptides with Pro or Ala residues in the second amino terminal position. Previously, we have experimentally demonstrated the existence of the serine protease domain in PI-PLC from *Bacillus cereus* - both by virtue of its proteolytic activity, and the inhibition of its native activity on phospholipids in the presence of serine protease inhibitors²². Furthermore, the specificity of the proteolytic activity indicated that it was a prolyl peptidase - thus, leading us to believe that DPP4 inhibitors should have a similar inhibitory effect on the PI-PLC enzyme. Table 1 shows the presence of a congruent motif in the PI-PLC protein with both Motif1 and Motif2. His32 and Asp67 are known to be a part of the active site scaffold in PI-PLC²². These proteins have completely different folds, and thus a superimposition (using both MUSTANG³⁴ and DECAAF³⁵) does not show any detectable similarity in their structures (Supplementary Figure 1). Figure 1 shows the active sites of these proteins, and the superimposition of these proteins

Table 1. Potential and spatial congruence of the active site residues in proteins queried using two motifs - Motif1 from Trypsin and Motif2 from DPP4. Rmsd1 and Rmsd2 are the root mean square deviation of the scaffold with respect to Motif1 and Motif2. DPP4 - dipeptidyl peptidase-IV, PI-PLC - phosphoinositide-specific phospholipase C, PLASE - human pancreatic lipase-Related Protein 2, GPASE - human gastric lipase, QC - glutaminyl cyclase. D = Pairwise distance in Å. PD = Pairwise potential difference. APBS writes out the electrostatic potential in dimensionless units of kT/e where k is Boltzmann's constant, T is the temperature in K and e is the charge of an electron.

PDB	Active site atoms (a,b,c,d)		ab	ac	ad	bc	bd	cd	Rmsd1	Rmsd2
TRYPSIN (1A0J)	D102,S195 H57,A56	D PD	7.8 -144.1	5.6 -39.2	2.9 -248.3	3.3 104.8	9.0 -104.3	6.9 -209.1	0	0.5
DPP4 (1N1M)	D708,S630 H740,V711	D PD	7.6 -154.4	5.4 124.4	2.6 -148.8	2.6 278.8	6.8 5.6	5.4 -273.2	0.5	0
PI-PLC (1PTD)	D67,S234 H32,I68	D PD	8.2 -93.7	6.2 39.7	4.1 -245.2	3.8 133.4	11.5 -151.5	9.2 -284.8	0.6	1.1
PLASE (2OXE)	D195,S171 H282,G235	D PD	7.7 -150.2	6.4 26.7	4.4 -132.1	3.0 176.9	6.7 18.2	5.8 -158.8	0.5	0.4
GPASE (1HLG) Motif1	D324,S153, H353,L326	D PD	7.5 -202.6	5.0 -15.0	2.9 -272.3	2.7 187.6	8.4 -69.7	6.2 -257.3	0.2	0.3
GPASE (1HLG) Motif2	D324,S153 H353,A327	D PD	7.5 -202.6	5.0 -15.0	2.6 -207.1	2.7 187.6	7.1 -4.5	5.3 -192.1	0.4	0.1
QC (3PB4)	D170,S187, H168,G224	D PD	7.5 -92.8	4.8 -16.5	3.4 -214.0	3.3 76.3	10.7 -121.2	8.0 -197.5	0.4	0.8

Figure 1. The active site residues in Trypsin, DPP4 and PI-PLC. (a) Trypsin (PDBid:1A0J) (b) DPP4 (PDBid:1N1M); (c) PI-PLC (PDBid:1PTD) (d) Superimposing the active site residues using DE-CAAF³⁵. The superimposition can be viewed in Superimposeproteins.p1m in [Dataset 1](#).

based on their catalytic residues³⁵. It can be seen that the closest non-polar residue to the catalytic triad in trypsin and PI-PLC (Ala56 in PDBid:1A0J, Ile68 in PDBid:1PTD) is differently placed from Val711 in DPP4 (PDBid:1N1M). This is also indicated by the greater RMSD (root mean square deviation) of the scaffold in PI-PLC to Motif2 as compared to Motif1. The differences in the position of peripheral residues is the source of the diverse specificities exhibited by these proteases. **Figure 2** shows the inhibition of PI-PLC using two gliptins - vildagliptin (LAF-237)²³ and K579²⁴. PI-PLC catalyzes hydrolysis of phospholipids to yield diacylglycerol and a phosphoryl alcohol. In the absence of inhibitors enzyme addition to the vesicle suspension causes an increase in turbidity due to vesicle aggregation (**Figure 2 a,c**). Aggregation in turn occurs as a result of formation of the enzyme endproduct diacylglycerol^{36,37}. A steady-state is reached under our conditions after 6–8 min. Addition of either LAF-237 (vildagliptin) or K579 leads to an obvious inhibition of the enzyme activity.

Dose-response curves for the inhibitors are shown in **Figure 2 (b,d)**. K579 is two orders of magnitude more potent than LAF-237 as a PI-PLC inhibitor, with half-maximal inhibitory concentrations IC_{50} respectively of 1 μ M and 100 μ M.

Phosphoinositide-specific phospholipase C inhibition data using the dipeptidyl peptidase-IV inhibitors K-579 and LAF-237

12 Data Files

<http://dx.doi.org/10.6084/m9.figshare.880620>

Querying a non-redundant set of human proteins using Motif1 and Motif2. Currently, the PDB database has about 25,000 human proteins. Using a identity cutoff of 50%, we chose a set of ~5000 proteins (**Supplementary Table 1**) as the target proteins.

Figure 2. PI-PLC inhibition using DPP4 inhibitors. (a,c) Time courses of enzyme activity in the presence of varying amounts of inhibitors, respectively LAF-237 and K579. The trace marked LIPOSOMES corresponds to a control in the absence of PI-PLC. (b,d) Dose-response effect of inhibitors on PI-PLC activity. Activity was computed as the extent of vesicle aggregation after 10 min enzyme activity.

Table 2 shows ten proteins which have significant matches with Motif1 and Motif2. Given the context of lipases, acute pancreatitis and GLP-1 based therapies, we picked two proteins - the human pancreatic lipase-related protein 2 (PDBid:2OXE)²⁶ and a human gastric lipase (PDBid:1HLG)²⁷ - to demonstrate the distinct possibility that these proteins might be inhibited by DPP4 inhibitors. Table 1 shows the congruence of the DPP4 motif to these proteins using Motif1 and Motif2. It is interesting to note that the gastric lipase (PDBid:1HLG) has a good match with both motifs - Leu326 in PDBid:1HLG is congruent to Ala56 in PDBid:1A0J, and Ala237 (PDBid:1HLG) is congruent to Val711 (PDBid:1N1M).

Since both these proteins are lipases (hydrolases), this congruence to Motif1 and Motif2 is expected based on our previous results with PI-PLC²². However, our methodology also detects other proteins, often with a completely different enzymatic mechanism from hydrolases. A glutaminyl cyclase (PDBid:3PB4)³², a transferase, has a significantly congruent domain with Motif1 (lesser congruence with Motif2, as indicated by the RMSD) (Table 1). Figure 3 shows the proximity of the promiscuous scaffold to the active site of the cyclase, and also the congruence of the scaffold to Motif1.

Docking vildagliptin to the PIPLC structure. Since there are no DPP4 structures solved which ligand K-579, a DPP4 protein structure in complex with vildagliptin (PDBid:3W2TA)³⁸ was used to dock vildagliptin to the PIPLC structure complexed with myo-inositol (PDBid:1PTG³⁹) using DOCLASP⁴⁰ (Figure 4). The Pymol script for visualizing the docking (SupplementaryPymol.p1m) is provided as [Supplementary information](#).

Statistics of atoms making contact with inhibitors. There are 76 unique DPP4 inhibitors, defined by three letter codes, for which the

Table 2. Best matches in the set of ~5000 human proteins. (a) Motif1 (Asp102, Ser195, His57, Ala56) from Trypsin (b) Motif2 (Asp708, Ser630, His740, Val711) from DPP4.

Motif	PDB	Description	CLASP Score
1	2ANY	Plasma kallikrein, light chain	0.028
1	2OQ5	Transmembrane protease, serine 11E	0.037
1	3U0V	Lysophospholipase-like protein 1	0.041
1	2ODP	Complement C2	0.060
1	1IMJ	CCG1-interacting factor B	0.065
1	3F6U	Vitamin K-dependent protein C heavy chain	0.065
1	1ELV	Complement C1S component	0.068
1	1MD8	C1R complement serine protease	0.068
1	1ORF	Granzyme A	0.070
1	1FJ2	Acyl protein thioesterase 1	0.071
2	1HLG	Gastric lipase	0.042
2	1SPJ	Kallikrein 1	0.114
2	2F83	Coagulation factor XI	0.120
2	1ZJK	Mannan-binding lectin serine protease 2	0.131
2	3QLP	Thrombin light chain	0.145
2	2QXI	Kallikrein-7	0.146
2	2XU7	Histone-binding protein RBBP4	0.174
2	2W2N	Proprotein convertase subtilisin/kexin type 9	0.180
2	2HEH	KIF2C protein	0.195
2	2ANY	Plasma kallikrein, light chain	0.197

Figure 3. A scaffold congruent to the active site of Trypsin (PDBid:1A0J) in a glutaminyl cyclase (PDBid:3PB4). (a) The active site residues are marked in magenta. They are seen to be proximal to the identified scaffold. (b) Superimposition of Motif1 and the scaffold in glutaminyl cyclase. The exact pairwise interatomic distance and electrostatic potential differences are specified in Table 1.

Figure 4. Docking vildagliptin to the PI-PLC structure in complex with myo-inositol (PDBid:1PTGA). Docking done using DOCLASP⁴⁰. The Pymol script for visualizing the docking (SupplementaryPymol.p1m) is provided as [Supplementary information](#).

ligand-DPP4 structure is solved ([Supplementary Table 2](#)). For uniformity, we chose the first four closest atoms from the protein that make contacts to the ligand, excluding hydrophobic interactions. [Table 3](#) shows the number of times each residue in DPP4 makes contact to the ligand. Three residues are ubiquitous in making contacts in all these ligands: Glu205, Glu206 and Tyr662 made contacts in 71, 68 and 63 ligands, respectively. Interestingly, Glu205 and Glu206 have been implicated as critical residues for the enzymatic activity of DPP4 through point mutations⁴¹. Note, that since only the first four residues were considered, these counts are conservative (and might be more). A recent study has found that inhibitors that bind to residues beyond the extensive subsite (defined as Val207, Ser209, Phe357 and Arg358) increases DPP4 inhibition, as compared to those inhibitors that form a covalent bond with Ser630³⁸. [Table 3](#) shows that very few inhibitors make such contacts. We created a library of motifs from these structures that can be used to query any protein using CLASP to determine the possibility that DPP4 inhibitors might bind to it ([Supplementary Table 3](#)), after removing equivalent ones to eliminate redundancy. This table shows the final list of 39 motifs (pruned from the initial 76); this is a comprehensive set of motifs that encapsulates the current knowledge about protein ligand interactions for the DPP4 enzyme. A facet of ligand binding that needs to be accounted for while choosing a motif is the spatial and electrostatic changes that can be induced by ligand binding. Thus, we obtain the residues involved in binding from the holo enzyme, but extract the motif values (pairwise distance and EPD) from the apo enzyme.

Discussion

The controversy regarding the side effects of the dpp4 inhibitors, particularly with respect to acute pancreatitis and pancreatic cancer, continues unabated. While some researchers feel that it is not acceptable to assume that 'absence of evidence is evidence of absence'^{42,43}, others believe that current data are not conclusive and the 'benefits by far outweigh the potential risks'¹⁶. Adding to the uncertainties are conflicting reports presented by different

groups²⁸⁻³¹. Notwithstanding the antagonistic views on the subject, it is unanimously accepted that current data are insufficient to establish a causal pathogenic effect of these drugs on such side effects⁴⁴.

Table 3. Number of times residues from the DPP4 enzyme ligand an inhibitor. Three residues - Glu205, Glu206 and Tyr662 - make contacts in 71, 68 and 63 ligands, respectively. Note, that since we only choose the first four residues based on proximity of the atoms closest to the ligand, these counts are conservative (and might be actually more).

Residue	Number of ligands
ARG125	11
GLU205	71
GLU206	68
VAL207	1
SER209	3
ARG358	6
TYR547	18
GLN553	1
TYR585	1
TRP629	1
SER630	10
TYR631	12
TYR662	63
ASN710	15

Various database studies have been undertaken in order to ascertain the effects of the GLP-1 therapies. Some studies ‘did not find an association between the use of exenatide or sitagliptin and acute pancreatitis’ with the caveat that the ‘limitations of this observational claims-based analysis cannot exclude the possibility of an increased risk’⁴⁵. On the other hand, other studies have shown that the use of ‘sitagliptin or exenatide increased the odds ratio for reported pancreatitis 6-fold as compared with other therapies’¹⁴. Further, they reported that ‘pancreatic cancer was more commonly reported among patients who took sitagliptin or exenatide as compared with other therapies’¹⁴. Although these studies concern the usage of both GLP-1 mimetics and the orally administered gliptins, and our study exclusively focusses on gliptins, and is not concerned with the GLP-1 mimetics data. The close relationship between chronic pancreatitis and pancreatic cancer is also a subject of intense research⁴⁶. Another administrative database study of US adults with type 2 diabetes reported increased odds of hospitalization for acute pancreatitis for patients undergoing GLP-1 based therapies sitagliptin¹³. Once again, such correlation of GLP-1 based therapies to acute pancreatitis is contested by other studies⁴⁷.

Our findings rationalize the elevated levels of serum lipase found in patients undergoing DPP4 inhibitor based therapies^{28,29}, keeping in mind that other studies contradict these reports^{30,31}. While several studies have reported that the GLP-1 mimetics do not induce pancreatitis in rats, mouse and/or monkey^{48–50}, these studies did not include DPP4 inhibitors, which are the compounds that might be responsible for interactions with pancreatic proteins according to our study. It is to be noted however that these mimetics may have other physiological effects and ‘the long-term consequences of sustained GLP-1 receptor activation in the human thyroid remain unknown and merit further investigation’⁵¹. Once again, the previous study⁵¹ has been challenged by another group who note that ‘findings previously reported in rodents may not apply to humans’⁵².

The orally administered gliptins differ in many aspects such as potency, excretion mechanism, target selectivity, half-life, metabolism and possible drug-drug interactions^{9,53,54}. This difference is also highlighted in the different concentrations of vildagliptin and K579 that inhibit PI-PLC. A recent study has also noted the differential off-target inhibition of enzymes by vildagliptin and sitagliptin using a high-throughput, multiplexed assay⁵⁵. Interestingly, the PI-PLC scaffold has a better match with the trypsin motif than with the DPP4 motif (Table 1). In order to be able to model these differences in our *in silico* search, it is important to be able to provide flexibility in the scoring mechanism.

To summarize, it has been noted in the case of GLP-1 based therapies that as ‘evidence of harm accumulates, but is vigorously discounted’ the ‘burden of proof now rests with those who wish to convince us of their safety’⁴³. Surveillance programs, real-life cohort studies and case-control studies can be supplemented by rational investigations of relevant proteins based on anecdotal reports⁵⁶. The methodology proposed in the current work, which specifically

demonstrates the effects of the DPP4 inhibitors, also presents a rational way of determining the inadvertent interactions of newly designed compounds with proteins, and thus prevent the recurrence of drug induced diseases being detected after considerable damage has already been inflicted on humans subjected to these drugs⁵⁷.

Materials and methods

In silico analysis

A comprehensive, non-redundant set of ~5000 human proteins (50% identity cutoff) was obtained from the PDB database⁵⁸. The CLASP package (<http://www.sanchak.com/clasp>) used for querying these proteins using motifs from trypsin and DPP4 is written in Perl on Ubuntu²⁰. Hardware requirements are modest - all results here are from a simple workstation (8GB ram), and runtimes for analyzing the ~5000 proteins was about 24 hours. Adaptive Poisson-Boltzmann Solver (APBS) and PDB2PQR packages were used to calculate the potential difference between the reactive atoms of the corresponding proteins^{59,60}. The APBS parameters and electrostatic potential units were set as described previously in Chakraborty *et al.*²⁰. All protein structures were rendered by PyMol (<http://www.pymol.org/>). Protein structures have been superimposed using MUSTANG³⁴ and DECAAF³⁵.

Protein, substrate and reagents

PI-PLC was purchased from Sigma. Vildagliptin (LAF-237) was obtained from Selleckchem, and K579 was obtained from Santa Cruz.

PI-PLC assay and inhibition using DPP4 inhibitors

Vesicle preparation and characterization. The appropriate lipids were mixed in organic solution, and the solvent was evaporated to dryness under N₂. Solvent traces were removed by evacuating the lipids for at least 2 hours. The lipids were then swollen in 10 mM Hepes, 150 mM NaCl, pH 7.5 buffer. Large unilamellar vesicles (LUV) were prepared from the swollen lipids by extrusion and sized by using 0.1 µm poresize Nuclepore filters, as described by Ahayauch *et al.*³⁶. LUV composition was egg phosphatidylcholine: egg phosphatidylethanolamine: cholesterol at a 2:1:1 mole ratio. The average size of LUV was measured by quasi-elastic light scattering, using a Malvern Zeta-sizer instrument. Lipid concentration, determined by phosphate analysis, was 0.3 mM in all experiments.

Aggregation Assay. Enzyme activity was assayed measuring enzyme-induced vesicle aggregation. All assays were carried out at 39°C with continuous stirring, in 10 mM Hepes, 150 mM NaCl buffer (pH 7.5), in the presence of 0.1% BSA for optimum catalytic activity. Enzyme concentration was 0.16 U/mL, and liposomal concentration was 0.3 mM. Lipid aggregation was monitored in a Cary Varian UV-vesicle spectrometer as an increase in turbidity (absorbance at 450 nm) of the sample, as described by Villar *et al.*³⁷. The data are average values of two closely similar experiments.

Analyzing known DPP4 inhibitors with solved structures. In order to obtain all known structures of DPP4 with inhibitors bound to the

active site, we did a search for the keyword dipeptidyl-peptidase on the PDB database, and choose proteins with DPP4 inhibitors as ligands. There are 76 such unique compounds (defined by three letter codes) that are reported to date (May 2014). We docked the DPP4 inhibitor to the PIPLC active site using DOCLASP⁴⁰.

Data availability

figshare: Phosphoinositide-specific phospholipase C inhibition data using the dipeptidyl peptidase-IV inhibitors K-579 and LAF-237, <http://dx.doi.org/10.6084/m9.figshare.880620>

Author contributions

SC, ARR and BA performed the experiments. All authors analyzed the data, and contributed equally to the writing and subsequent refinement of the manuscript.

Competing interests

No competing interests were disclosed.

Grant information

FMG thanks the Spanish Ministerio de Ciencia e Innovacion for grant No. BFU 2012-36241, and the University of the Basque Country for grant No. IT 849-13. BJ and RV acknowledge financial support from Tata Institute of Fundamental Research (Department of Atomic Energy). Additionally, BJR is thankful to the Department of Science and Technology for the JC Bose Award Grant. BA extends gratitude to the University of Iceland Research Found for supporting the project financially. AMD wishes to acknowledge grant #12-0130-SA from California Department of Food and Agriculture CDFA PD/GWSS Board. MO was supported in part by a Grant-in-aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology, Japan; (grant No. 21790431). The work in Liege was supported by an IUAP program funded by the Belgian federal government.

Acknowledgements

We are grateful to Jean-Marie Frère, Centre for Protein Engineering, Université de Liège, Institut de Chimie B6, Sart Tilman, B-4000 Liège, Belgium for critical inputs.

Supplementary information

Supplementary Pymol scripts. Click here to access the files. <http://dx.doi.org/10.5256/f1000research.3002.s40929>

Supplementary Figure 1. Superimposition of trypsin (PDBid:1A0J - magenta), dipeptidyl peptidase-IV (PDBid:1N1M - yellow) and phosphoinositide-specific phospholipase C (PDBid:1PTD - cyan). It is seen that there is no structural similarity in the two proteins. (a) Using MUSTANG³⁴. (b) Using DECAAF³⁵.

Supplementary Table 1. PDB IDs of ~5000 human proteins analyzed in this study.

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 2X7A 2X7F 2X8A 2XA6 2XB1 2XB2 2XC7 2XDG 2XDP 2XDV 2XEB 2XES 2XEU 2XFN 2XHI 2XIJ
 2XIO 2XJY 2XMR 2XN4 2XN6 2XOC 2XR6 2XRC 2XRI 2XRW 2XS6 2XSQ 2XSS 2XST 2XSW 2XSZ
 2XTC 2XTD 2XTP 2XU3 2XU7 2XUB 2XUS 2XV5 2XVS 2XVT 2XW9 2XXZ 2XY1 2XY2 2XYC 2XZE
 2XZG 2XZP 2XZZ 2Y05 2Y1H 2Y1N 2Y1Y 2Y23 2Y25 2Y29 2Y2A 2Y3J 2Y3K 2Y3L 2Y43 2Y4Q 2Y4T
 2Y5C 2Y6E 2Y73 2Y7B 2Y7J 2Y8G 2Y95 2Y96 2Y9A 2Y9B 2Y9C 2Y9D 2Y9U 2YAD 2YAN 2YB6 2YBX
 2YCF 2YD0 2YD6 2YD9 2YDL 2YDY 2YEX 2YF0 2YG2 2YGD 2YGN 2YGO 2YGQ 2YH0 2YH1
 2YHF 2YHW 2YKG 2YKO 2YLE 2YLM 2YMB 2YMK 2YPD 2YPR 2YPS 2YQG 2YQI 2YQK 2YQL
 2YQP 2YQQ 2YQR 2YR3 2YRA 2YRB 2YRC 2YRE 2YRG 2YRL 2YRN 2YRO 2YRP 2YRQ 2YRT
 2YRV 2YRY 2YRZ 2YS0 2YS2 2YS4 2YS8 2YS9 2YSA 2YSC 2YSH 2YSJ 2YSL 2YSM 2YSQ 2YSR 2YST
 2YSX 2YT4 2YT7 2YT8 2YT9 2YTC 2YTU 2YTW 2YTX 2YTY 2YU1 2YU3 2YU6 2YU8 2YU9
 2YUA 2YUC 2YUD 2YUF 2YUH 2YUJ 2YUK 2YUM 2YUN 2YUQ 2YUR 2YUS 2YUU 2YUW 2YUX
 2YUY 2YUZ 2YVI 2YVQ 2YVR 2YW8 2YWK 2YX8 2YXM 2YXT 2YY0 2YYN 2YYO 2YZ8 2Z0B 2Z0U
 2Z0W 2Z14 2Z15 2Z17 2Z3Q 2Z5D 2Z5E 2Z5K 2Z6E 2Z6H 2Z6O 2ZAJ 2ZB4 2ZEJ 2ZFH 2ZFU 2ZFY
 2ZG1 2ZG2 2ZHN 2ZJ3 2ZKM 2ZMF 2ZND 2ZNR 2ZOU 2ZQ 2ZT5 2ZV2 2ZV6 2ZV3 3A03
 3A1A 3A1B 3A1F 3A1J 3A2A 3A4U 3A6N 3A77 3A7I 3A98 3A99 3AAF 3ABD 3ABH 3ADL 3AFA 3AGV
 3AGY 3AHQ 3AIH 3AJ4 3AKM 3AL2 3AL5 3AN2 3AOX 3AP1 3AP9 3APA 3AQG 3AQI 3AQQ 3ASK
 3ASL 3AU4 3AV1 3AV2 3AVR 3AY5 3AYW 3AZE 3AZF 3AZG 3AZH 3AZI 3AZJ 3AZK 3AZL 3AZM
 3AZN 3B0T 3B2D 3B5H 3B6E 3B6H 3B6R 3B6U 3B7K 3B7X 3B7Y 3B83 3B84 3B8K 3B93 3B95 3B9C
 3BBB 3BCH 3BCZ 3BDL 3BE8 3BEJ 3BER 3BFN 3BFO 3BG9 3BGS 3BGV 3BHD 3BHY 3BI7 3BIY
 3BJ4 3BJ5 3BJ9 3BJC 3BJU 3BKB 3BL9 3BO2 3BO3 3BO4 3BO5 3BOR 3BPJ 3BPT 3BPU 3BQ7 3BQO
 3BQP 3BRB 3BRV 3BS9 3BSB 3BSU 3BSX 3BTB 3BTX 3BTY 3BTZ 3BU0 3BU8 3BUC 3BUX 3BVO
 3BWY 3BXW 3BYI 3BZH 3C0I 3C1V 3C1X 3C2I 3C2K 3C2L 3C2M 3C3R 3C5C 3C5E 3C5F 3C5G 3C5H
 3C5K 3C5N 3C5R 3C5V 3C6K 3C6W 3C7X 3C8X 3C9Q 3CAF 3CB2 3CBB 3CBZ 3CEG 3CEK 3CH4
 3CI9 3CJJ 3CJW 3CKK 3CLZ 3CMY 3CO6 3COA 3COG 3COK 3COO 3CPF 3CQC 3CQV 3CRD 3CRY
 3CTR 3CTZ 3CU7 3CUL 3CUN 3CUQ 3CVF 3CW1 3CW3 3CWW 3CX2 3CXL 3CYY 3CZH 3D06 3D0A
 3D1N 3D2N 3D2Q 3D2S 3D32 3D34 3D3J 3D3K 3D3L 3D3M 3D4J 3D59 3D6M 3D7C 3D8B 3D8D 3D9H
 3D9N 3D9S 3D9T 3DAD 3DAI 3DAK 3DAL 3DB3 3DB5 3DCY 3DD2 3DDS 3DDT 3DDU 3DEM 3DH1
 3DJ9 3DK9 3DKM 3DKP 3DLJ 3DLM 3DLQ 3DLS 3DLX 3DPL 3DRX 3DRZ 3DSH 3DTC 3DWB 3DWD
 3DXE 3DXT 3DYD 3DYN 3DYT 3DZU 3DZY 3E00 3E04 3E0G 3E0J 3E11 3E1R 3E21 3E3R 3E46 3E4C
 3E6U 3E77 3E7E 3E9K 3E9L 3E9V 3EAB 3EAP 3EAY 3EAZ 3EBB 3EBQ 3EC8 3ECM 3ECR 3ED7
 3EDH 3EDU 3EDV 3EDY 3EG3 3EGA 3EGI 3EGN 3EGZ 3EH1 3EH2 3EHR 3EHW 3EIJ 3EJH 3ELB
 3ELO 3EMW 3ENP 3EO2 3EOP 3EP0 3EPG 3EPI 3EPZ 3EQ5 3EQC 3EQT 3ERB 3ERY 3ETO 3EU9
 3EVI 3EW8 3EWS 3EWY 3EX7 3EXE 3EY6 3EYI 3EZQ 3F02 3F04 3F0W 3F11 3F1P 3F1R 3F21 3F22
 3F23 3F2K 3F31 3F3S 3F4M 3F59 3F50 3F66 3F6K 3F6Q 3F6U 3F6Y 3F70 3F7Q 3F81 3F8U 3F9M 3F9X
 3FAU 3FAY 3FB2 3FBK 3FBY 3FCI 3FCX 3FD5 3FDO 3FDR 3FDW 3FE2 3FE3 3FE4 3FEA 3FED
 3FEG 3FFL 3FFM 3FFN 3FG7 3FGH 3FHR 3FHT 3FIA 3FIB 3FK2 3FKC 3FL2 3FL7 3FLG 3FLV 3FMO
 3FME 3FMZ 3FO5 3FRR 3FRT 3FRV 3FS1 3FSO 3FVO 3FVS 3FVY 3FW3 3FX0 3FXT 3FY1 3G07
 3G0H 3G2F 3G2S 3G36 3G4E 3G4G 3G5C 3G5P 3G6V 3G6X 3G6Y 3G73 3G8S 3G8T 3G96 3G9C 3G9Y
 3GA1 3GA3 3GAU 3GAX 3GBJ 3GD8 3GDH 3GDX 3GF9 3GG6 3GGE 3GHG 3GHM 3GI0 3GJ0 3GJW
 3GKJ 3GL6 3GLK 3GM3 3GOV 3GQC 3GQQ 3GR4 3GRO 3GV3 3GV5 3GV7 3GV8 3GYL 3H0H 3H1D
 3H40 3H4B 3H4D 3H63 3H6N 3H7H 3H8K 3H8O 3H8Q 3H8R 3H8V 3H8X 3H8Z 3H91 3H95 3H9E 3H9Y
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 3HQC 3HQI 3HR0 3HRN 3HRO 3HSH 3HTM 3HTU 3HU3 3HUP 3HW8 3HWN 3HWT 3HX0 3HX3 3HXO
 3HXQ 3HY3 3HYG 3HYM 3HZJ 3I00 3I08 3I28 3I2B 3I2N 3I2V 3I33 3I35 3I3C 3I4A 3I4U 3I4W 3I5R 3I6C
 3I6U 3I6X 3I84 3I8A 3IA8 3IAI 3IAR 3IBJ 3ICU 3IDV 3IEI 3IEZ 3IF8 3IFA 3IGK 3IGL 3IH7 3IHJ 3IHR 3IHX
 3IIO 3I17 3I1J 3I1N 3I1J 3IKK 3IKL 3ILZ 3IN5 3IO2 3IOH 3IOL 3IQ2 3IQU 3IR3 3IRQ 3IRR 3ISB 3ISC
 3ISD 3ISQ 3ITU 3IU1 3IU5 3IU6 3IUF 3IUG 3IUY 3IV1 3IVV 3IWL 3IWN 3IWP 3IX0 3IXS 3JOA 3J3D
 3J3F 3JPN 3JPO 3JPP 3JPQ 3JPR 3JPS 3JPT 3JQH 3JUD 3JUI 3JUY 3JXF 3JXH 3JZY 3K05 3K0J
 3K0W 3K1R 3K1W 3K1Z 3K26 3K2A 3K2J 3K2O 3K35 3K6G 3K6S 3K7I 3KAN 3KAT 3KB5 3KCI 3KDF
 3KDV 3KG5 3KGR 3KGV 3KH0 3KHF 3KJD 3KJO 3KJP 3KMD 3KN1 3KN6 3KNB 3KNV 3KOV 3KQ0
 3KQG 3KQI 3KQS 3KRM 3KS3 3KS9 3KSY 3KT9 3KTM 3KTU 3KTV 3KUP 3KUQ 3KUS 3KUZ 3KVH
 3KVO 3KVQ 3KVW 3KW6 3KY9 3KZ8 3KZD 3L00 3L11 3L15 3L1X 3L2C 3L2P 3L3C 3L42 3L43 3L46
 3L4C 3L4G 3L4H 3L4Y 3L50 3L5H 3L5I 3L5K 3L6A 3L6B 3L6X 3L81 3L9Q 3LCY 3LD6 3LE4 3LF5 3LFV
 3LGD 3LH5 3LHR 3LJB 3LJU 3LJW 3LK9 3LL6 3LLH 3LLK 3LLM 3LLP 3LLU 3LM5 3LMN 3LNY
 3LOF 3LPW 3LQ9 3LQH 3LQM 3LQV 3LRA 3LRE 3LRI 3LRN 3LRQ 3LRR 3LRU 3LS8 3LUC 3LUI
 3LVR 3LWE 3LWK 3LXX 3LY5 3LYR 3LZB 3M03 3M06 3M1D 3M5B 3M66 3M7P 3M9J 3MAO 3MAX
 3MAZ 3MB3 3MB4 3MBY 3MCB 3MCE 3MCF 3MDA 3MDC 3MDF 3MDG 3MDI 3MDM 3MEW 3MFK
 3MGH 3MGI 3MIJ 3MJG 3MJK 3MK1 3MK4 3MK6 3MMY 3MNG 3MOP 3MOS 3MPX 3MQ4 3MQ7
 3MQI 3MQL 3MQM 3MQP 3MR2 3MR3 3MR5 3MR6 3MSH 3MT5 3MTC 3MTR 3MTS 3MTT 3MU6
 3MUJ 3MUM 3MUP 3MUR 3MUT 3MUV 3MVA 3MVB 3MWD 3MX7 3MXH 3MXN 3MXO 3MYI 3N00

Supplementary Table 2. Residues of DPP4 closest to the bound ligand with possible hydrogen bonds.

Interactions sorted based on the distance. N: Number of atoms in the ligand, R/A/LA/D: Residue number/Atom of the residue/Atom of ligand/distance between the interacting atoms (in Å). For example, 'E205/OE1/N25/2.7' means that the atom OE1 from Glu205 is at 2.7 Å from the N25 atom of W94 in PDBid:3VJLA. For uniformity, we choose the first four closest atoms. This might result in choosing some atoms which are unlikely to form a hydrogen bond (for example, in PDBid:4J3JA S209/OG is at 4.8 Å from NAQ).

PDB	HET	N	R/A/LA/D	R/A/LA/D	R/A/LA/D	R/A/LA/D
3VJLA	W94	33	E205/OE1/N25/2.7	E206/OE1/N25/2.8	N710/ND2/O33/2.9	Y662/OH/O33/3
2AJ8A	SC3	26	E205/OE2/N13/2.7	E206/OE1/N13/3	Y631/N/O23/3.1	Y547/OH/N7/3.4
2RGUA	356	35	E205/OE2/N27/3	Y662/OH/N27/3.1	Y631/N/O10/3.1	E206/OE2/N27/3.1
4A5SA	N7F	37	E205/OE2/N18/2.7	E206/OE2/N18/2.7	Y662/OH/N18/2.8	Y631/N/O26/3
2QTBA	474	32	E205/OE2/N6/2.7	N710/ND2/O7/2.8	E206/OE1/N6/2.8	R358/NE/N56/2.8
2OGZA	U1N	24	Y631/N/O25/3	E206/OE1/N12/3.1	R125/NH2/O15/3.1	E205/OE2/O15/3.3
2JIDA	GVB	24	E206/OE2/N20/2.8	E205/OE2/N20/2.9	Y662/OH/N20/3	R125/NH1/O25/3.8
2I78B	KIQ	31	Y662/OH/N/3	E205/O/O/4.1	E206/OE1/O/4.2	R669/NH2/O/4.4
3H0CA	PS4	32	E205/OE2/N21/2.7	Y662/OH/N21/2.9	E206/OE2/N21/2.9	Q553/N/O3/3
2AJLI	JNH	24	S630/OG/N3/2.3	E206/OE2/N2/2.5	Y547/OH/N3/2.6	E205/OE2/N2/2.7
2BUBA	FPB	28	E206/OE2/N18/2.5	E205/OE2/N18/2.9	Y662/OH/N18/3	Y547/OH/O16/4.3
4DSAA	D1C	29	E206/OE2/NAY/2.6	E205/O/OBC/3.1	Y662/OH/NAY/3.1	Y585/OH/NAI/3.9
2OPHA	277	23	E205/OE2/N33/2.7	N710/ND2/O32/2.8	Y662/OH/N33/3.1	E206/OE2/N33/3.1
1RWQA	5AP	27	Y662/OH/N21/2.5	E206/OE2/N21/2.8	E205/OE2/N23/2.9	R125/NH2/N1/3.4
2QJRA	PZF	29	E205/OE2/N20/2.6	R358/NE/O18/2.8	E206/OE2/N20/2.9	Y662/OH/N20/3
2FJPA	S14	31	E205/OE2/N30/2.7	N710/ND2/O32/2.8	E206/OE2/N30/2.8	Y547/OH/O33/2.8
2OAEA	AIL	21	E203/OE2/N2/2.8	E204/OE2/N2/2.8	N711/ND2/O8/3.1	Y663/OH/N9/3.1
3G0CA	RUF	27	E205/OE1/N9/3	E206/OE1/N9/3.2	Y631/N/O23/3.4	Y547/OH/N12/3.6
3C43A	315	31	E205/OE2/N6/2.8	Y662/OH/N6/3	N710/ND2/O5/3	E206/OE2/N6/3
3BJMA	BJM	23	S630/OG/N23/2.4	E205/OE2/N7/2.7	E206/OE2/N7/2.7	Y547/OH/O15/2.8
3O95A	01T	26	E206/OE2/N13/2.5	E205/OE1/N13/2.8	Y662/OH/N13/2.8	R125/NH1/O19/3
3G0GA	RUM	24	E205/OE1/N24/2.9	E206/OE1/N24/3.1	Y631/N/O8/3.2	R125/NH2/N17/3.3
2G5PA	ADF	29	S630/OG/N22/2.4	Y662/OH/N8/3.1	Y547/OH/N22/3.1	E206/OE2/N7/3.1
2BUC	008	26	E206/OE2/N10/2.7	Y662/OH/N10/2.8	E205/OE2/N10/3	Y547/OH/O13/4.5
2QOEA	448	29	E206/OE2/N20/2.7	E205/OE2/N20/2.9	Y662/OH/N20/2.9	Y547/OH/O22/4.6
2OLEA	KR2	30	E206/OE2/NAM/2.7	Y662/OH/NAM/3.6	E205/OE2/NAM/4	Y547/OH/OAP/4.5
3KWFA	B1Q	27	E205/OE2/N21/2.7	N710/ND2/O19/2.7	Y662/OH/N21/3	R125/NH2/O19/3
3SX4A	KXA	58	Y662/OH/N25/2.7	E206/OE2/N25/2.7	E205/OE2/N25/2.8	R125/NH1/O26/3.1
2ONCA	SY1	27	E205/OE1/N1/2.6	Y631/N/O17/3.1	Y547/OH/N18/3.2	E206/OE1/N1/3.4
2I03B	AXD	29	S630/OG/N14/2.4	E206/OE1/N1/2.8	Y662/OH/O16/2.9	Y547/OH/N14/3
3KWJA	23Q	27	E205/OE2/N17/2.6	Y662/OH/N17/2.8	E206/OE2/N17/2.8	S209/OG/O19/3.3
3CCCA	7AC	21	E205/OE1/N20/2.5	Y662/OH/N20/2.7	E206/OE2/N20/3.2	Y631/N/N9/3.3
3SWWA	KXB	25	E205/OE2/N21/2.7	Y662/OH/N21/2.8	E206/OE2/N21/2.9	R125/NH2/N19/3.5
4G1FA	OWG	24	E206/OE2/N9/2.8	Y662/OH/N9/2.9	Y547/OH/N2/3.1	Y631/N/O20/3.1
3C45A	317	30	E205/OE2/N6/2.8	E206/OE2/N6/2.8	Y662/OH/N6/3	Y547/OH/N29/3.7

PDB	HET	N	R/A/LA/D	R/A/LA/D	R/A/LA/D	R/A/LA/D
2G63B	AAF	29	S630/OG/N18/2.4	E205/OE2/N7/2.6	Y662/OH/N8/3.1	Y547/OH/N18/3.1
1X70A	715	28	E206/OE2/N20/2.7	E205/OE2/N20/2.8	Y662/OH/N20/2.8	S209/OG/N27/3.9
2GBIA	XIH	29	E204/OE2/N14/2.3	Y632/N/O/2.8	E203/OE2/N14/3	Y663/OH/N14/3.1
3G0BA	T22	25	E205/OE1/N13/2.5	R125/NH2/N24/3.1	Y631/N/O26/3.2	E206/OE1/N13/3.3
2IITA	872	28	E205/OE2/N20/2.7	Y662/OH/N20/2.8	E206/OE2/N20/2.9	N710/OD1/N20/4.5
4JH0A	1MD	27	Y662/OH/N16/2.7	E206/OE2/N16/2.7	Y547/OH/O1/2.8	E205/OE2/N16/2.9
4LKOA	1WH	25	Y662/OH/N/2.7	E206/OE2/N/2.8	E205/OE2/N/2.9	Y547/OH/O2/3
2RIPA	34Q	25	N710/ND2/O1/2.6	E205/OE2/N3/2.8	Y662/OH/N3/2.8	E206/OE1/N3/2.8
3QBJA	NXZ	25	Y662/OH/N18/2.7	E206/OE2/N18/2.7	N710/ND2/O25/2.8	E205/OE2/N18/2.9
3HACA	361	23	Y662/OH/N23/2.7	E205/OE2/N23/2.8	E206/OE1/N12/4.2	N710/OD1/N23/4.3
3VJMA	W61	32	E205/OE1/N28/2.7	E206/OE1/N28/2.7	Y662/OH/O57/2.9	N710/ND2/O57/2.9
3O9VA	10T	23	Y547/OH/O15/2.5	E206/OE2/N19/2.6	Y662/OH/N19/2.7	E205/OE1/N19/2.8
4DSZA	DC3	26	E206/OE2/NAM/2.8	E205/OE2/NAM/3.1	Y662/OH/NAM/3.1	S209/OG/NAR/4.7
4J3JA	D3C	30	E206/OE2/NAM/2.8	E205/OE2/NAM/3.1	Y662/OH/NAM/3.3	S209/OG/NAQ/4.8
4DTCA	D5C	33	E206/OE2/NAM/2.7	E205/OE2/NAM/3.1	Y662/OH/NAM/3.3	R669/NH2/OAQ/4.2
3OPMA	LUI	28	E205/OE1/N18/2.7	Y662/OH/N18/2.8	E206/OE2/N18/2.9	W629/O/N27/3
2OAGB	DLI	31	E205/OE2/N22/2.5	Y662/OH/N22/2.6	E206/OE2/N22/2.9	R358/NE/O1/3.2
2GBGA	1AD	19	S631/OG/N12/2.4	E203/OE2/N14/2.7	Y548/OH/N12/3	E204/OE2/N14/3.1
2HHAA	3TP	26	E205/OE2/N6/2.7	E206/OE2/N6/2.7	Y662/OH/N6/2.9	N710/ND2/O5/2.9
2QT9A	524	31	E205/OE2/N19/2.6	E206/OE2/N19/2.8	Y662/OH/N19/2.9	N710/ND2/O20/2.9
2OQVA	MA9	32	E206/OE2/N27/2.7	Y662/OH/N27/3	R358/NE/O4/3.1	E205/OE2/N27/3.3
3F8SA	PF2	26	E205/OE2/N3/2.5	Y662/OH/O7/2.8	N710/OD1/O7/3	E206/OE2/N3/3.2
2AJBA	0QG	24	S630/OG/N2/2.4	E205/OE2/N/2.7	HIS740/NE2/O2/2.9	Y662/OH/O/3
2G5TA	ACF	26	S630/OG/N22/2.4	E205/OE2/N7/2.6	Y662/OH/O3/3	N710/ND2/O3/3
3NOXA	6A5	28	E205/OE2/N16/2.4	E206/OE2/N16/2.7	Y662/OH/N16/3	R125/NH2/N4/3.7
3W2TA	LF7	22	S630/OG/N2/2.4	E205/OE1/N12/2.8	Y662/OH/O20/3	E206/OE2/N12/3
3D4LA	605	26	E205/OE2/N15/2.6	R358/NE/O42/2.8	Y662/OH/N15/2.9	V207/O/N41/2.9
2QKYA	13Z	26	S630/OG/O2/2.1	E205/O/O4/2.5	Y547/OH/O2/2.6	E206/OE1/O4/2.8
3Q8WA	AZV	38	R125/NH1/O/2.5	E206/OE2/NAG/2.6	Y662/OH/NAG/2.8	E205/OE2/NAG/2.9
3EIOA	AJH	33	Y585/OH/OBD/2.6	E205/OE2/NBG/2.7	Y662/OH/NBG/2.9	E206/OE2/NBG/2.9
3Q0TA	LGE	26	Y662/OH/N21/2.6	E205/OE2/N21/2.7	E206/OE2/N21/2.9	R125/NH1/O22/3.4
2P8SA	417	58	E205/OE2/N38/2.8	E206/OE2/N38/2.9	Y662/OH/N38/3.2	S209/OG/N34/3.4
2OQIB	GGO	28	E205/OE2/N/2.4	Y662/OH/N/2.7	E206/OE2/N/2.9	R358/NE/O/3.2
4PNZA	2VH	28	E205/OE2/N/2.7	E206/OE2/N/2.8	Y662/OH/N/2.9	Y547/OH/O/3.2
3VJKA	M51	30	E205/OE1/N21/2.9	Y662/OH/O30/2.9	E206/OE1/N21/2.9	N710/ND2/O30/3
3OC0A	B2Q	23	E205/OE2/NS/2.8	S209/OG/OB/2.9	Y662/OH/NS/3.4	E206/OE2/NS/3.5
4N8DA	2KS	24	E206/OE2/N10/2.7	E205/OE2/N10/2.8	Y662/OH/N10/2.8	N710/OD1/N10/4.5
4N8EA	2KV	22	E205/OE2/N15/2.7	E206/OE2/N15/2.7	Y662/OH/N15/2.8	N710/OD1/N15/4.3
2IIVA	565	24	E205/OE2/N20/2.7	Y662/OH/N20/2.8	E206/OE2/N20/2.9	N710/ND2/N20/4.4
3HABA	677	27	E205/OE2/N23/2.7	Y662/OH/N23/2.7	E206/OE1/N12/4.3	N710/OD1/N23/4.4
2I3ZA	LIR	27	E203/OE2/N18/2.5	Y632/N/O9/2.7	Y548/OH/N6/3.4	E204/OE2/N18/3.4

Supplementary Table 3. Library of non-redundant motifs. This library of motifs can be used to query any protein using CLASP to determine the possibility that DPP4 inhibitors might bind to it.

PDB	Motif Name	Motif
3VJLA	2OQVA1	GLU205/OE1 GLU206/OE1 TYR662/OH ASN710/ND2
2AJ8A	2OQVA2	GLU205/OE2 GLU206/OE1 TYR547/OH TYR631/N
2RGUA	2OQVA3	GLU205/OE2 GLU206/OE2 TYR631/N TYR662/OH
2QTBA	2OQVA4	GLU205/OE2 GLU206/OE1 ARG358/NE ASN710/ND2
2OGZA	2OQVA5	ARG125/NH2 GLU205/OE2 GLU206/OE1 TYR631/N
2JIDA	2OQVA6	ARG125/NH1 GLU205/OE2 GLU206/OE2 TYR662/OH
2I78B	2OQVA7	GLU205/O GLU206/OE1 TYR662/OH ARG669/NH2
3H0CA	2OQVA8	GLU205/OE2 GLU206/OE2 GLN553/N TYR662/OH
2AJLI	2OQVA9	GLU205/OE2 GLU206/OE2 TYR547/OH SER630/OG
2BUBA	2OQVA10	GLU205/OE2 GLU206/OE2 TYR547/OH TYR662/OH
4DSAA	2OQVA11	GLU205/O GLU206/OE2 TYR585/OH TYR662/OH
2OPHA	2OQVA12	GLU205/OE2 GLU206/OE2 TYR662/OH ASN710/ND2
1RWQA	2OQVA13	ARG125/NH2 GLU205/OE2 GLU206/OE2 TYR662/OH
2QJRA	2OQVA14	GLU205/OE2 GLU206/OE2 ARG358/NE TYR662/OH
2FJPA	2OQVA15	GLU205/OE2 GLU206/OE2 TYR547/OH ASN710/ND2
2OAEA	2OQVA16	GLU205/OE2 GLU206/OE2 TYR662/OH ASN711/ND2
3G0CA	2OQVA17	GLU205/OE1 GLU206/OE1 TYR547/OH TYR631/N
3O95A	2OQVA18	ARG125/NH1 GLU205/OE1 GLU206/OE2 TYR662/OH
3G0GA	2OQVA19	ARG125/NH2 GLU205/OE1 GLU206/OE1 TYR631/N
2G5PA	2OQVA20	GLU206/OE2 TYR547/OH SER630/OG TYR662/OH
3KWFA	2OQVA21	ARG125/NH2 GLU205/OE2 TYR662/OH ASN710/ND2
2I03B	2OQVA22	GLU206/OE1 TYR547/OH SER630/OG TYR662/OH
3KWJA	2OQVA23	GLU205/OE2 GLU206/OE2 SER209/OG TYR662/OH
3CCCA	2OQVA24	GLU205/OE1 GLU206/OE2 TYR631/N TYR662/OH
4G1FA	2OQVA25	GLU206/OE2 TYR547/OH TYR631/N TYR662/OH
2G63B	2OQVA26	GLU205/OE2 TYR547/OH SER630/OG TYR662/OH
2IITA	2OQVA27	GLU205/OE2 GLU206/OE2 TYR662/OH ASN710/OD1
2RIPA	2OQVA28	GLU205/OE2 GLU206/OE1 TYR662/OH ASN710/ND2
3HACA	2OQVA29	GLU205/OE2 GLU206/OE1 TYR662/OH ASN710/OD1
3O9VA	2OQVA30	GLU205/OE1 GLU206/OE2 TYR547/OH TYR662/OH
4DTCA	2OQVA31	GLU205/OE2 GLU206/OE2 TYR662/OH ARG669/NH2
3OPMA	2OQVA32	GLU205/OE1 GLU206/OE2 TRP629/O TYR662/OH
2AJBA	2OQVA33	GLU205/OE2 SER630/OG TYR662/OH HIS740/NE2
2G5TA	2OQVA34	GLU205/OE2 SER630/OG TYR662/OH ASN710/ND2
3W2TA	2OQVA35	GLU205/OE1 GLU206/OE2 SER630/OG TYR662/OH
3D4LA	2OQVA36	GLU205/OE2 VAL207/O ARG358/NE TYR662/OH
2QKYA	2OQVA37	GLU205/O GLU206/OE1 TYR547/OH SER630/OG
3EIOA	2OQVA38	GLU205/OE2 GLU206/OE2 TYR585/OH TYR662/OH
2I3ZA	2OQVA39	GLU205/OE2 GLU206/OE2 TYR547/OH TYR631/N

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Current Peer Review Status:

Version 2

Reviewer Report 20 January 2015

<https://doi.org/10.5256/f1000research.6371.r7383>

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Mark D Gorrell

Molecular Hepatology, Centenary Institute, Newtown, NSW, Australia

Thank you to the authors for developing this paper.

I have some further comments.

1. The primary issue now is the speculation in the title.

The title seeks to extrapolate the obtained data on two compounds to suggest that it is applicable to all DPP-IV inhibitors.

That is, the speculation of this paper is that the presented data is relevant to an entire drug class. The comments and the title should be restricted to one or two of the compounds that were studied in this paper. Moreover, K-579 is not a diabetes drug. In this context, the title needs changing to avoid ambiguity.

I suggest:

"The dipeptidyl peptidase IV inhibitor vildagliptin used in type 2 diabetes inhibits a phospholipase C: a case of promiscuous scaffolds in proteins."

or

"The dipeptidyl peptidase IV inhibitors vildagliptin and K-579 inhibit a phospholipase C: a case of promiscuous scaffolds in proteins."

2. This study complements the much broader work using focused, direct technology for measuring and detecting off-target inhibition. That paper is published in Nature Chemical Biology in 2014 ([Bachovchin et al. 2014](#)). That study similarly showed that vildagliptin inhibits enzymes other than DPP-IV. That study showed that DPP4 inhibitors differ, such that sitagliptin does not inhibit other enzymes.

The authors need to comment and restrict their conclusions to the compounds that they studied rather than imply that DPP-IV inhibiting compounds that they did not study, such as sitagliptin, have similar characteristics to the compounds that they did study.

3. The data of this study is biochemical yet 16 of the cited references concern the safety of DPP-IV inhibition. The manuscript now carefully does not draw a link to drug safety; the title needs to do the same.
4. As the paper is focused upon DPP-IV structure and function, more papers on this topic could be cited and linked with the data. For example, the author's amendment mentions contacts in DPP-IV at Glu205, Glu206 and Tyr662. The authors could state that Glu205 and Glu206 have been shown to be essential for catalysis by DPP-IV and cite the paper [Abbott *et al.* \(1999\)](#).

Competing Interests: This reviewer recently received a speaker honorarium from Boehringer Ingelheim, which manufactures linagliptin.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 28 Jan 2015

Sandeep Chakraborty, Tata Institute of Fundamental Research, Mumbai, India

We would like to thank you for your positive comments, and your informative suggestions.

We agree with your suggested change in the title. In the latest version, we have also cited the research you have brought to our attention.

Competing Interests: No competing interests were disclosed.

Version 1

Reviewer Report 26 March 2014

<https://doi.org/10.5256/f1000research.3236.r4249>

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Mark D Gorrell

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The successful targeting of DPP4 using small molecule compounds to treat type 2 diabetes has attracted a great deal of attention towards the study of this protease.

The authors applied sophisticated techniques that they have developed in order to discover that two DPP4 inhibitors, including one that is in limited clinical use, can to some extent inhibit the activity of a bacterial lipase (PI-PLC). Many lipases and esterases and hydrolases including DPP4 and related enzymes use the *alpha/beta* hydrolase fold and the authors show how this related protein topology can place the residues in positions that are sufficiently similar to interact with an inhibitor.

The major difficulty with this paper is that it attempts to connect these data with possible clinical outcomes. No evidence for such a link is presented. Therefore, the title and much of the conclusions need to be modified so that they reflect the data without speculation.

Two inhibitors of DPP4, LAF237 and K-579, were studied. K-579 is not in clinical use. LAF237 is licensed in Europe and is known to exhibit some inhibition of the DPP4-related proteases DPP8 and DPP9. The extent of inhibition of DPP8 and DPP9 by LAF237 is believed not to have physiological effects in humans. The IC₅₀ of LAF237 on DPP9 is less than 0.01 mM. The IC₅₀ of LAF237 on bacterial PI-PLC is 0.1mM, which is close to the lower limit of detection of inhibition of an enzyme. No mammalian homolog of PI-PLC was examined.

The literature that the authors cite to suggest that DPP4 inhibition might be detrimental for human health, particularly the pancreas, is data on sitagliptin or exenatide. Exenatide is not a DPP4 inhibitor and sitagliptin is quite different to LAF237, both in protease specificity and in chemical structure. The contact points of LAF237 and sitagliptin in the catalytic site of DPP4 differ considerably. The authors present no data on sitagliptin or any other DPP4 inhibitor (other than LAF237) that is in the clinic.

The images of overlaid catalytic triads of various enzymes presented in Fig 1 and Fig 3 need to be depicted in 3D in order to evaluate how close they are in 3D. Intermolecular distances should be shown on these figures. To convince the reader that LAF237 sits into and makes contacts with enzymes other than DPP4, we need to see the compound docked into the structure of each enzyme of interest.

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 10 Dec 2014

Sandeep Chakraborty, Tata Institute of Fundamental Research, Mumbai, India

We would like to thank you for taking the time to review this paper, and also for your insightful comments. We also apologize for the inordinate time taken to respond to your comments. A lot of this time was spent in understanding docking methods, instead of blindly applying this to the problem at hand. A by-product of this learning process was the

implementation of a new method (DOCLASP) for docking molecules to proteins¹. We have docked vildagliptin to the PI-PLC structure complexed with myo-inositol using DOCLASP. Based on your suggestion, we have also done a comprehensive analysis of all 76 known DPP4 structures liganded to inhibitors till date.

Please find out detailed responses to your comments below.

- *The successful targeting of DPP4 using small molecule compounds to treat type 2 diabetes has attracted a great deal of attention towards the study of this protease. The authors applied sophisticated techniques that they have developed in order to discover that two DPP4 inhibitors, including one that is in limited clinical use, can to some extent inhibit the activity of a bacterial lipase (PI-PLC). Many lipases and esterases and hydrolases including DPP4 and related enzymes use the alpha/beta hydrolase fold and the authors show how this related protein topology can place the residues in positions that are sufficiently similar to interact with an inhibitor. The major difficulty with this paper is that it attempts to connect these data with possible clinical outcomes. No evidence for such a link is presented. Therefore, the title and much of the conclusions need to be modified so that they reflect the data without speculation.*

We have tried to keep away from taking sides on the clinical outcomes, since that is not our forte. Also, we believe our title is innocuous in that context - it just speaks of promiscuous scaffolds. We only highlight that if (and only if) our data of PIPLC inhibition holds true for human lipases, then it might provide some arguing points for those worried about the side effects of these drugs.

For example, we say 'The reported elevated levels of serum lipase, although contested, could be rationalized by inhibition of lipases reported here'. If you could kindly point out specifically any speculations that is unwarranted, we will modify those.

- *Two inhibitors of DPP4, LAF237 and K-579, were studied. K-579 is not in clinical use. LAF237 is licensed in Europe and is known to exhibit some inhibition of the DPP4-related proteases DPP8 and DPP9. The extent of inhibition of DPP8 and DPP9 by LAF237 is believed not to have physiological effects in humans.*

Since this study does not emphasize on the clinical relevance of the inhibitions (but on the methodology of finding such interactions), and we are not a group specializing in diabetes, we believe the choice of the inhibitors would not alter our reasoning our conclusions.

- *The IC₅₀ of LAF237 on DPP9 is less than 0.01 mM. The IC₅₀ of LAF237 on bacterial PI-PLC is 0.1mM, which is close to the lower limit of detection of inhibition of an enzyme.*

We agree to this point. However, K-579 was inhibiting even at nanomolar concentrations.

- *No mammalian homolog of PI-PLC was examined.*

We are currently evaluating that possibility.

- *The literature that the authors cite to suggest that DPP4 inhibition might be detrimental for human health, particularly the pancreas, is data on sitagliptin or exenatide. Exenatide is not a DPP4 inhibitor and sitagliptin is quite different to LAF237, both in protease specificity and in chemical structure.*

We were referring to the inhibitor part of the data, but that point needs to be made explicit as you have correctly pointed out. Also, we agree that the possible difference of sitagliptin with LAF237 needs to be stated. We have modified the text to include these criticisms. Once again, we reiterate we intend not to comment on clinical outcomes or debates, but to suggest a rational methodology to act as a guide for tests that look for possible interactions.

- *The contact points of LAF237 and sitagliptin in the catalytic site of DPP4 differ considerably. The authors present no data on sitagliptin or any other DPP4 inhibitor (other than LAF237) that in is the clinic.*

We have included a comprehensive study on the contact points of various inhibitors. Once again, this does not negate any of our conclusions.

- *The images of overlaid catalytic triads of various enzymes presented in Fig 1 and Fig 3 need to be depicted in 3D in order to evaluate how close they are in 3D.*

The 3D images of the superimposition of these enzymes are not pleasing to the eye, since they lack structural homology. However, we have added a PyMol script in case someone wishes to do that (Superimposeproteins.p1m). The script specifies the color coding of the residues.

- *Intermolecular distances should be shown on thee figures.*

Once again, we think that the intermolecular distances clutter the figure. The superimposition gives an approximate idea of the congruence. The exact values are specified in Table 1. We have modified the legend of Fig.3 to specify that.

- *To convince the reader that LAF237 sits into and makes contacts with enzymes other than DPP4, we need to see the compound docked into the structure of each enzyme of interest.*

As mentioned previously, we have docked sitagliptin to PI-PLC using DOCLASP¹. We have provided the Pymol script as supplementary data to help visualize the docking. There is no solved structure where LAF237 inhibits DPP4.

Once again, we are thankful for the comments. We hope that we have addressed your concerns by the changes that we have made, and that the manuscript will be found suitable in the modified form.

References

1. Chakraborty S. *DOCLASP* - Docking ligands to target proteins using spatial and electrostatic congruence extracted from a known holoenzyme and applying simple geometrical transformations [v2; ref status: awaiting peer review, <http://f1000r.es/4pb>] *F1000Research* 2014, **3**:262 (doi: [10.12688/f1000research.5145.2](https://doi.org/10.12688/f1000research.5145.2))

Competing Interests: No competing interests were disclosed.

Reviewer Report 06 March 2014

<https://doi.org/10.5256/f1000research.3236.r3818>

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Rodney Rouse

Division of Applied Regulatory Science, Center for Drug Evaluation and Research, U.S. Food and Drug Administration, Silver Spring, MD, USA

Disclaimer: I lack the protein chemistry expertise to comment on the assumptions and protein chemistry used in the computational method described in this article.

The title and abstract are appropriate. The overall experimental design is simple but strong and well suited for this project. The methods were generally well described. The conclusions are not overstated and any implications are justified based on the presented data. The article is very well written.

This is a very interesting study that uses a previously defined computational method, Catalytic Active Site Prediction (CLASP), that compares structural and charge similarities of catalytic sites to identify functionally similar proteins. This methodology was used to assess the potential for adverse events based on off target effects of the inhibitors of DPP-IV. Using CLASP, the authors had previously identified a *Bacillus cereus* phosphoinositide specific phospholipase-C (PI-PLC) as similar in active catalytic site to the enzyme, DPP-IV. They used laboratory techniques to verify this finding.

In the present study, the authors demonstrated the ability of two separate DPP-IV inhibitors to significantly reduce the activity of this PI-PLC in the lab. Subsequent to this experimentation, the authors returned CLASP to identify catalytic sites in other proteins that might also be inhibited by DPP-IV inhibitors thereby yielding unforeseen inhibition and biological effects. As applied to the case of DPP-IV inhibitors, which are not extremely specific, the authors identify a number of other proteins that could be promiscuously impacted by DPP-IV inhibitors thereby providing mechanisms for unexpected adverse events. Although the significance of DPP-IV inhibitor related adverse events has yet to be determined, the fact that changes have been reported non-

clinically and clinically are undeniable. Eventually, the benefit of these molecules may far outweigh their associated risks, but the authors provide a potential path forward for investigation of unexpected events with this class of drug. If contradictory reports persist, this path may require further illumination.

The approach is theoretically similar to using structural similarities to identify off target receptor binding and consequent biological effects, an expanding approach in safety assessment and in identification of mechanisms for adverse events in the pharmaceutical lifecycle. Similarly, this method could be predictive for off target effects and suggest what those effects might be. However, whether this is a method that can be generally applicable to other molecules is beyond my ability to comment and the scope of this work.

Comments/Suggestions:

1) Were the inhibition experiments done in duplicate, triplicate, etc? Some slight expansion of the protocols would help with attempts to replicate.

Competing Interests: No competing interests were disclosed.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 10 Mar 2014

Adela Rendón-Ramírez, Unidad de Biofísica CSIC UPV, Spain

Dear Dr Rouse,

We would like to thank you for taking the time and reviewing our paper. Your positive comments encourage us to further our research in this area.

We concur with your statement - "*Eventually, the benefit of these molecules may far outweigh their associated risks*". And it is our endeavor to improve the accuracy and generality of our method through different compounds. We would specifically like to highlight another case of antagonist binding identified through CLASP, although in this case most alkaline phosphatases were not affected - [Chakraborty et al.\(2012\)](#)

The data for PI-PLC inhibition using DPP4 inhibitors, as shown in Figure 2, are average values of two closely similar experiments. We will revise the manuscript to include this point when we hear from another referee.

Best regards,

Sandeep Chakraborty and Adela Rendón-Ramírez

Competing Interests: No competing interests were disclosed.

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