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Design, synthesis, and structure-activity relationship studies of 6H-benzo[b]indeno[1,2-d] thiophen-6-one derivatives as DYRK1A/CLK1/ CLK4/haspin inhibitors†

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A series of sulfur-containing tetracycles was designed and evaluated for their ability to inhibit protein kinase DYRK1A, a target known to have several potential therapeutic applications including cancers, Down syndrome or Alzheimer's disease. Our medicinal chemistry strategy relied on the design of new compounds using ring contraction/isosteric replacement and constrained analogy of known DYRK1A inhibitors, thus resulting in their DYRK1A inhibitory activity enhancement. Whereas a good inhibitory effect of targeted DYRK1A protein was observed for 5-hydroxy compounds 4i-k ($IC_{50} = 35-116$ nM) and the 5-methoxy derivative 4e ($IC_{50} = 52 \text{ nM}$), a fairly good selectivity towards its known DYRK1B off-target was observed for 4k. In addition, the most active compound 4k, having an ATP-competitive mechanism of action, proved to be also a potent inhibitor of CLK1/CLK4 (IC50 = 20 and 26 nM) and, to a lesser extent, of haspin (IC₅₀ = 76 nM) kinases. In silico docking studies within the DYRK1A, CLK1/CLK4 and haspin ATP binding sites were carried out to understand the interactions of our tetracyclic derivatives 4 with these targets. Antiproliferative activities on U87/U373 glioblastoma cell lines of the most potent compound 4k showed a moderate effect (IC $_{50}$ values between 33 and 46 μ M). Microsomal stabilities of the designed compounds 4a-m were also investigated, showing great disparities, depending on benzo[b]thiophene ring 5-substitution.

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Introduction

Since the approval of imatinib in 2001¹ and the clinical successes of this first rationally-designed kinase inhibitor (KI) for the treatment of chronic myelogenous leukemia² and gastrointestinal stromal tumors,3 many KIs have been developed for the treatment of various cancers,4 also addressing the problems of selectivity and resistance

phenomena to KI treatments. ⁵ To date, more than 70 KIs have been clinically approved in the U.S.,6 with different mechanisms of action, mainly targeting the ATP binding site (with few molecules acting as allosteric modulators). Currently, the main applications of KIs focus on oncology,⁵ which remains one of the most challenging public health issues and a leading cause of death for the World population.7

(NGU), Newgiza, km 22 Cairo-Alexandria Desert Road, 12577 Cairo, Egypt ^f School of Life and Medical Sciences, University of Hertfordshire Hosted by Global Academic Foundation, New Administrative Capital, Cairo, 11865, Egypt g Universite Claude Bernard Lyon 1, CNRS UMR 5305, LBTI, ECMO Team, Institut de Biologie et Chimie des Protéines, 7 Passage du Vercors, 69367, Lyon Cedex 07, France † Electronic supplementary information (ESI) available: ¹H and ¹³C NMR spectra of synthesis intermediate alcohols 7a-m, ketones 6a-m, and final tetracyclic compounds 4a-m, effect/dose curves for complementary kinase profiling, antiproliferative effects (U373 and U87 glioblastoma cells) for compound 4k and molecular modelling data. See DOI: https://doi.org/10.1039/d4md00537f ‡ These authors contributed equally to this work.

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In this context, the search for new therapeutic/druggable protein kinase targets remains a tremendous area of research and KIs were also developed by industrial and academic research groups for potential applications not only in cancer but also in infectious diseases, 8-13 auto-immune pathologies such as multiple sclerosis, ¹⁴ Parkinson's ^{15,16} and Alzheimer's diseases.^{17,18} More specifically, the dual-specificity tyrosine regulated kinase 1A (DYRK1A) has gained considerable attention due to its involvement in numerous diseases¹⁹ such as diabetes, 20,21 viral infections 22,23 and central nervous disorders like Down syndrome and Alzheimer's disease. 24-26

Many DYRK1A inhibitors, both from natural and synthetic origins, were developed, 27,28 such as harmine, INDY, its acetylated prodrug Pro-INDY or its methylated derivative 1 (also known as TG003), PST-001, 29 7-azaindole DANDY-5a, 30 the tetracyclic derivative 231 or leucettinibs, the most advanced and selective DYRK1A inhibitors reported to date.32

While being in some cases very active, some off-target cross-inhibition was sometimes observed for these molecules, 33,34 which stimulated the scientific community to develop new chemical entities with enhanced potency and

Inspired by the structure of chromeno[3,4-b]indoles 3³⁵ (Fig. 2), we planned on synthesizing the original 9-thiaindeno[1,2-a]inden-10-ones 4, after chromene contraction to indenone and isoelectronic NH substitution by a sulfur atom. These original structures are also constrained analogs of the corresponding "open form", benzothiophenylacetophenones 5 (Fig. 2), known DYRK1A/CLK1 dual inhibitors, acting as pre-mRNA splicing modulators. 36,37

Harmine
$$IC_{50} = 80 \text{ nM}$$

HOOC

HOOC

N

HOOC

HOOC

HOOC

N

HOOC

HOOC

N

HOOC

Fig. 1 Structures of some known DYRK1A inhibitors (IC₅₀ for DYRK1A is indicated).

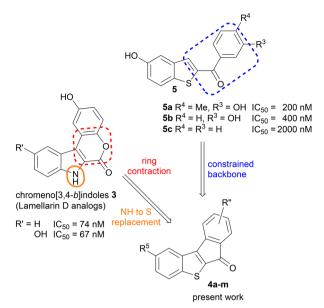


Fig. 2 Drug design strategy for the preparation of tetracycles 4 (IC₅₀ for DYRK1A are indicated).

In the work described herein, we wish to report the synthesis and biological evaluations of a series of these new derivatives 4a-m, initially designed to inhibit DYRK1A.

Results and discussion

Chemistry

The syntheses of the target products 4a-m relied on a palladium-catalyzed annulation reaction of precursors 6a-m. These substrates were prepared after oxidation of the corresponding alcohols 7a-m, which were itself obtained using the addition of 2-benzothiophenyl lithium anions from 9a-c onto methoxy ortho-iodobenzaldehydes 8a-e (Fig. 3).

Functionalized benzo[b]thiophenes 9 were prepared by acidic cyclization of diethoxy acetals 10a, b, obtained from corresponding para-thiophenols 11a, b³⁸⁻⁴¹ (Scheme 1) and a

Fig. 3 Synthetic strategy for the preparation of tetracyclic targets 4.

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Scheme 1 Access to benzo[b]thiophenes 9. Reagents and conditions: (a) bromoacetaldehyde diethyl acetal, K₂CO₃, acetone, rt, 18 h, 96% for 10a $(R^5 = OMe)$, 69% for **10b** $(R^5 = F)$. (b) Polyphosphoric acid, chlorobenzene, 130 °C, 18 h, 85% for **9a** ($R^5 = OMe$), 60% for **9b** ($R^5 = F$).

subsequent BBr3-mediated demethylation on 9a/silylation sequence for the preparation of silyl derivative 9c (R^5 = OTBDMS).42,43

Ortho-Iodobenzaldehydes 8a-e were prepared according to various protocols: electrophilic iodination of meta-methoxy anisaldehyde 12 into 8d44 or pyridinium dichromate PDC (Cornforth reagent) mediated oxidation of ortho-iodobenzyl alcohols 13a-c, e⁴⁵ into 8a-c, e (Schemes 2 and 3). Whereas aldehyde 8a was obtained after PDC/silica oxidation of commercially available 2-iodobenzyl alcohol 13a in 98% vield (Scheme 3), compound 8b was obtained from 3-methoxy 2-iodobenzyl alcohol 13b, first synthesized using a nucleophilic iodination (n-BuLi/I2) on 3-methoxy benzyl alcohol 14 (Scheme 2).46

The other benzylic alcohols were prepared using a two steps sequence:45 diazotation/diazonium iodination on 4-

Scheme 2 Access to ortho-iodobenzaldehydes 8b,d. Reagents and conditions: (a) I₂/H₅IO₆, acetic acid/H₂SO₄, 70 °C, 16 h, 46%. (b) n-BuLi, I₂, Et₂O, 0 °C then rt, 2 h, 63%. (c) PDC, silica, CH₂Cl₂, rt, 6 h, 76%.

Scheme 3 Access to ortho-iodobenzaldehydes 8a,c,e. Reagents and conditions: (a) NaNO₂/HCl_{aq}, KI, 0 °C then 90 °C, 1.5 h, quant. for 16a, quant. for 16b. (b) BH₃·Me₂S, B(OMe)₃, THF, rt, 16 h, 65% for 13c, 47% for 13e. (c) PDC, silica, CH₂Cl₂, rt, 6 h, 98% for 8a, 89% for 8c, 61% for 8e.

Benzo[b]thiophene	Aldehyde reagent			Yield
R ⁵	R"	compound	Product	%
Н	3-OMe	8b	7a	75
Н	4-OMe	8c	7b	74
Н	5-OMe	8d	7c	68
Н	6-OMe	8e	7d	38
OMe	Н	8a	7e	88
OMe	3-ОМе	8b	7f	60
OMe	4-OMe	8c	7g	82
OMe	5-OMe	8d	7h	91
OTBDMS	Н	8a	7i	64
OTBDMS	4-OMe	8c	7j	91
OTBDMS	5-OMe	8d	7k	54
OTBDMS	6-OMe	8e	71	20
F	5-OMe	8d	7m	51

Scheme 4 Synthesis of bis(het)arylcarbinols 7a-m.

and 6-methoxy anthranilic acids 15a, b, followed by reduction of the benzoic acid functions of 16a, b into an alcohol using BH₃, yielding the iodo compounds 13c, e (Scheme 3).

The two key partners were then engaged in the next step: the lithium anion was generated at position 2 of benzo[b] thiophene 9a-c, after deprotonation using n-BuLi at low temperature, and was trapped by ortho-iodobenzaldehydes 8a-e to give carbinols 7a-m in 20-91% yield (Scheme 3). Yield disparities were indeed noticed: although good to very good yields for the preparation of most alcohols were observed, low yields were especially observed when using the ortho, ortho'-disubstituted aldehyde 8e. Steric hindrance resulting from the presence of both iodo and methoxy groups on this electrophile may be responsible for the low 20% and 38% yields (Scheme 4).

The bis(het)arylcarbinols 7 were hereafter oxidized into the corresponding ketones 6 using stoichiometric amounts of manganese dioxide in 67-96% yield (Scheme 5 and Table 1). These substrates 6 then underwent a palladium-catalyzed

Scheme 5 Preparation of keto derivatives 6 and tetracyclic compounds 4. Reagents and conditions: (a) MnO₂ 6 eq., acetonitrile, rt, 6 h, 67-96%. (b) Pd(OAc)₂ 5 mol%, Cy₃P·HBF₄ 10 mol%, K₂CO₃, DMF, 130 °C, 16 h, 51-87%.

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Entry		R ⁵	0	% inhibition a,b at 1 μ M	IC_{50} for DYRK1A a,b in nM
1	4a	$R^5 = H$	R" = 10-OMe	DYRK1A <5%	nd
				DYRK1B < 5%	
2	4b	$R^5 = H$	R'' = 9-OMe	DYRK1A <5%	nd
				DYRK1B <5%	
3	4c	$R^5 = H$	R'' = 8-OMe	DYRK1A <5%	nd
				DYRK1B <5%	
4	4d	$R^5 = H$	R'' = 7-OMe	DYRK1A 23%	nd
				DYRK1B 7%	
5	4e	$R^5 = OMe$	R'' = H	DYRK1A 91%	52
				DYRK1B 68%	
6	4f	$R^5 = OMe$	R'' = 10-OMe	DYRK1A 28%	nd
				DYRK1B <5%	
7	4g	$R^5 = OMe$	R'' = 9-OMe	DYRK1A 25%	nd
				DYRK1B <5%	
8	4h	$R^5 = OMe$	R'' = 8-OMe	DYRK1A <5%	nd
				DYRK1B <5%	
9	4i	$R^5 = OH$	R'' = H	DYRK1A 98%	105
				DYRK1B 89%	
10	4j	$R^5 = OH$	R'' = 9-OMe	DYRK1A 99%	116
				DYRK 1B 93%	
11	4k	$R^5 = OH$	R'' = 8-OMe	DYRK1A 97%	35
				DYRK1B 78%	
12	41	$R^5 = OH$	R'' = 7-OMe	DYRK1A 93%	54
				DYRK1B 78%	
13	4m	$R^5 = F$	R'' = 8-OMe	DYRK1A <5%	nd
				DYRK1B < 5%	

^a Calculated after the measurement of residual kinase activity, using a functional, radiometric kinase assay. ^b Values are the mean of two experiments with SD \leq 20%. nd: not determined.

annulation reaction,⁴⁷ thus leading to the desired tetracycles 4a-m in good to very good yields (Scheme 5 and ESI† Table S2).

Inhibitory properties towards DYRK1A/DYRK1B and R⁵/R" structure-activity relationship studies

A primary screening of the tetracyclic derivatives 4a-m inhibitory properties was first carried out on DYRK1A, together with its off-target DYRK1B, at a 1 µM concentration, using a radiometric assay with Woodtide substrate peptide.⁴⁸

As shown above (Table 1), some interesting hits were identified, indicating a sharp structure-activity relationship depending on the molecular diversity brought by R⁵ (H, OMe, OH and F) and R" (H or OMe) substitution on the tetracyclic scaffold.

Low DYRK1A inhibitions were observed with compounds **4a–d**, without any substituent on R^5 of the benzo[b]thiophene ring (Table 1, entries 1–4).

On the other hand, compounds 4f and 4g bearing methoxy groups on R5 displayed fairly low 25-32% inhibition at 1 µM (Table 1, entries 6 and 7), whereas no inhibition was detected for compound 4h (Table 1, entry 8). Surprisingly, compound 4e exhibited significant 91% DYRK1A inhibition at 1 µM, meaning that the introduction of a methoxy group at this position without any other substitution on the indenone ring could be useful to have a potent inhibitor (IC₅₀ for DYRK1A = 52 nM, Table 1, entry 5). It should be noted that 4e was the sole active derivative without a hydroxy group.

DYRK1A inhibitory activity for hydroxy compounds 4i-l was higher than 90% at 1 µM (Table 1, entries 9-12) and these results encouraged us to determine their IC50s. We were pleased to see that the potencies of compounds 4k and 4l against DYRK1A were quite high (IC50 = 35 and 54 nM, respectively) and, to a lesser extent, that the same tendency was observed for 4i and 4j (IC₅₀ = 105 and 116 nM, respectively). These results demonstrated that higher potencies can be reached by introducing a hydroxyl group at R⁵ position, in combination with a methoxy group at position 5 of the indenone moiety (Table 1, entry 11). The presence of a phenolic moiety on DYRK1A inhibitors was already reported in the literature 49,50 as for example INDY, DANDY-5a (Fig. 1), derivatives 3b (R' = OH) and 5 (Fig. 2).

A comparison of the "open form" 5c activity ($R^3 = R^4 = H$, IC_{50} (DYRK1A) = 2000 nM, Fig. 2) with its rigidified analog 4i $(IC_{50} (DYRK1A) = 105 \text{ nM})$ showed that constraining the third cycle was a successful strategy to improve DYRK1A inhibition.

Finally, compound 4m was synthesized to explore an isosteric replacement of the hydroxyl by a fluorine atom.⁵¹⁻⁵³

For all the compounds 4a-m, residual DYRK1B activity was determined at 1 µM concentration and, across the five most active compounds 4e, i-l (IC50s for DYRK1A ranged from 35 to 116 nM), a marked DYRK1B cross-inhibition was observed (68 to 93%, Table 1, entries 5, 9-12). However, the most potent derivative 4k against DYRK1A was amongst the least active DYRK1B co-inhibitors of this series (78% inhibition at 1 μM, Table 1, entry 11).

ATP competition of 4k was evaluated by measuring residual DYRK1A activity upon treatment with increasing concentrations of ATP, in the presence of a 50 nM concentration of 4k. Inhibition decreases with increasing ATP concentration as shown in ESI† Fig. S1, clearly indicating an ATP-competitive mechanism of action, as described for other literature compounds (Fig. 1).

Kinase selectivity study

In order to evaluate the off-target activity of our lead compound 4k, a complementary kinase profiling was then carried out at a 0.35 µM concentration (Table 2), i.e. 10-fold its IC₅₀. As significant disparities have been noted in the literature between fluorescence resonance energy transfer (FRET)-based and radiometric assays,28 some of the kinase activities were quantified by both techniques, operated by ThermoScientific/ Invitrogen and Eurofins/CEREP, respectively.

Using the FRET-based kinase assays (Z'-LYTE™/Adapta® activity assays or LanthaScreen europium kinase binding assay, see Table 2 footnotes), four hits with more than 50% inhibition were observed amongst the 21 selected kinases for our study: CLK4, DYRK1B, DYRK2 and haspin (Table 2).

Cross-inhibition for DYRK1A inhibitors was frequently observed with CLK1 and CLK4;28 hence, the low inhibition of CLK1 by 4k (16% inhibition at 0.35 µM, confirmed by its modest 1080 nM IC50 value) appeared suspicious, prompting

us to evaluate the inhibition of this protein kinase, using a radiometric activity assay. This second technique allowed us to demonstrate that compound 4k was in fact a potent CLK1 inhibitor, too, with a very low 20 nM IC₅₀ value.

Our first hypothesis to tentatively explain this difference is that the 6*H*-benzo[*b*]indeno[1,2-*d*]thiophen-6-one scaffold displays intrinsic fluorescent properties that could interfere with the FRET measurements. Nonetheless, as no "warnings flags" indicating such an interference were detected during the "test compound interference" evaluation, we can assume that the marked difference could be attributed by different assay conditions (e.g. protein kinase and substrate concentrations), as previously outlined in the literature.²⁸

For the three other impacted protein kinases (crossvalidation was not realized for DYRK2, IC₅₀ = 186 nM), results obtained by FRET techniques were corroborated by the radiometric activity assays.

The inhibitory effect of compound 4k against DYRK1B was proved to be moderate, both determined with Z'-LYTE FRET activity assay (IC50 = 206 nM) and functional radiometric test (47% inhibition of kinase activity at 0.35 μM). Furthermore, compound 4k is a moderate DYRK2 inhibitor but also a strong haspin inhibitor, as attested by both the FRET LanthaScreen Eu binding assay (IC₅₀ = 28 nM) and the activity radiometric evaluation ($IC_{50} = 76$ nM). As expected, 4k also strongly inhibits CLK4 in addition to CLK1, with low IC50 values of 14 nM (FRET-based binding assay) and 26 nM (functional radiometric test), respectively (Table 2).

Altogether, the selectivity profiling proved that compound 4k was a mixed DYRK1A/CLK1/CLK4/haspin inhibitor, thus corroborating trends already observed with similar architectures and these DYRK1A targets.36,50,54,55 In contrast, none of the other challenging off-targets in the screening panel was significantly inhibited, suggesting a reasonable "group selectivity" for the identified targets.

Table 2 Kinase selectivity profiling of compound 4k at 0.35 μM

Kinase	% inhibition/(IC_{50} [nM])	Kinase	% inhibition/(IC_{50} [nM])
CDK5/p25	8 ^a	EGFR (ErbB1)	0^a
CLK1	$16^a (1080^a) \\ 93^d (20^d)$	GSK3B (GSK3 beta)	2^a
CLK2	34^a	GSG2 (haspin)	$95^b (28^b) 88^d (76^d)$
CLK3	7^a	MLCK (MLCK2)	15 ^c
CLK4	$95^{c} (14^{c})$ $91^{d} (26^{d})$	HIPK1 (Myak)	0^a
CSNK1D (CK1 delta)	2^a	NTRK2 (TRKB)	0^a
CSNK2A1 (CK2 alpha 1)	2^a	PIM1	0^a
STK17A (DRAK1)	42^c	SRPK1	6 ^a
DYRK1B	$57^a (206^a) $ 47^d	SRPK2	0^a
DYRK2	$66^{c} (186^{c})$	STK33	8 ^c
DYRK3	5 ^a		

^a Z'-LYTE kinase activity assay. ^b Adapta kinase activity assay. ^c LanthaScreen kinase binding assay. ^d Radiometric kinase assay.

On the other side, dual/multiple kinase inhibitors could emerge as interesting approaches to cure cancers, 56-58 and could involve DYRK/CLK protein kinases⁵⁹ such as CLK1, 60-63 CLK4⁶²⁻⁶⁴ or the relatively underexplored but promising haspin kinase.65

Given that DYRK1A was previously identified as a promising target for a potential glioblastoma treatment, 49,66-69 we have chosen to evaluate some of our most potent compounds on these specific cell lines.

Antiproliferative effects on glioblastoma cells

The cellular effects of the most potent inhibitor 4k were determined by measuring growth inhibition following treatment with this compound in comparison to the less active derivative 4i and the reference compound harmine.⁷⁰ Dose-response curves allowed us to determine the IC50 on the two cell lines U373^{67,68} and U87^{68,70-73} (see ESI†), as DYRK1A proved to play a crucial role for cell proliferation and invasion of glioblastoma cells. 49,69,71,73

These studies showed that compound 4i (DYRK1A IC50 = 105 nM) had no significant effect on cell proliferation towards both glioblastoma cell lines U373 and U87 (Table 3, entry 1) whereas our most potent inhibitor 4k (DYRK1A IC₅₀ = 35 nM) exhibited a moderate anti-proliferative activity (Table 3, entry 2). Harmine also showed a moderate activity in both cell lines as well (Table 3, entry 3).

Harmine has a similar kinase selectivity profile as our compound 4k, and their effects on U87 and U373 cell lines growth require further exploration to discern whether they are mainly caused by DYRK1A inhibition alone or by crossinhibition of DYRK1A, CLK1, CLK4, and haspin.

Microsomal stability

In order to evaluate the potential druggability of this new family of DYRK/CLK/haspin inhibitors, we assessed their in vitro stability using rat liver microsomes (Table 4).

One can observe that 7- and 10-methoxy derivatives of 6Hbenzo[b]indeno[1,2-d]thiophen-6-one scaffold are rapidly metabolized as shown with 4a, 4d, 4f and 4l. 2-Hydroxy substitutions (4i-l) showed poor stability with fast conversion in our assay system whereas their methoxy equivalents were less sensitive to microsomal degradation as for 4e, 4g and 4h, except for 4d and 4l, bearing methoxy in

Table 3 Cell viability of compound 4i, k and harmine on glioblastoma cells U373 and U87

Entry	Compound	U373 ^a	U87 ^a
1	4i	>100 µM	>100 µM
2	4k	$32.8 \pm 5.0 \mu\text{M}^b$	$45.9 \pm 3.8 \mu \text{M}^b$
3	Harmine	$19.6 \pm 4.7 \mu M^{c}$	$16.0 \pm 5.1 \mu M^{c}$

^a IC₅₀: a sample's concentration which produces a 50% reduction in cell proliferation. ^b Mean of 6 independent experiments. ^c Mean of 4 independent experiments.

Table 4 Metabolic stability of 4a-m, determined on rat liver microsomes

Entry	Compound	$t^{\frac{1}{2}}\left(\min ight)$	CL _{int} (µL min ⁻¹ mg ⁻¹)
1	4a	6.5 ± 0.5	355.5 ± 26.2
2	4b	33.7 ± 2.8	68.8 ± 5.7
3	4c	24.4 ± 0.8	94.8 ± 3.0
4	4d	< 5.0	>500
5	4e	21.7 ± 1.1	106.5 ± 5.2
6	4f	< 5.0	>500
7	4g	25.3 ± 3.0	92.4 ± 10.8
8	4h	18.9 ± 0.5	122.0 ± 2.9
9	4i	< 5.0	>500
10	4j	<u></u> a	a
11	4k	< 5.0	>500
12	41	< 5.0	>500
13	4m	16.8 ± 1.2	93.9 ± 32.7

^a Possible inhibition of microsomes – see text for more information.

7- or 10-positions. Introduction of a 2-fluoro substituent (4m) did not improve stability against microsomal digestion. Interestingly, 4j was rapidly degraded to 50% of its initial amount then plateaued for the rest of the assay, suggesting an inhibitory mechanism by 4j (or its metabolite) against microsomes.

Docking studies

To gain insights into the binding mode of the synthesized compounds, molecular docking was performed using one of the described X-ray structures of DYRK1A (PDB ID: 5AIK). Prior to docking, every ligands, cofactors and additional interacting proteins were removed from the structure, and preparation of the protein was done using Molecular Operating Environment (MOE).⁷⁴ Each tested ligand (4a-m) was prepared for docking using MOE. Docking was performed using HERMES-GOLD.75

The DYRK1A surfaces were generated and a superposition of the docking results for all the synthesized compounds 4a-m was established (Fig. S2†). The comparison between all compounds showed significant positional homology, with the exception of compound 4b, which was flipped compared to the others (Fig. S2 and S3†).

A comparative study of the interaction modes of the five best ligands was carried out (Fig. 4). From these results, four protein residues were identified as stabilizing the ligand-protein complex, namely: Ile165, Glu203, Glu239 and Leu241. These similarities are consistent with the observed biological activities of the prepared compounds. The interactions between the molecular tetracyclic scaffolds with Glu239 and Leu241 are the most preserved over all structures. The carbonyl group is engaged with Leu241 by a strong H-bond, and the sulfur atom connects with the Glu239 backbone oxygen through a sigma* interaction. Surprisingly, the usual observed H-bonding with Lys188^{76,77} in DYRK1A was not observed with compounds 4a-m. This could be explained by the tandem sulfur-carbonyl sigma* and carbonyl-Leu214-NH strong interactions. For some

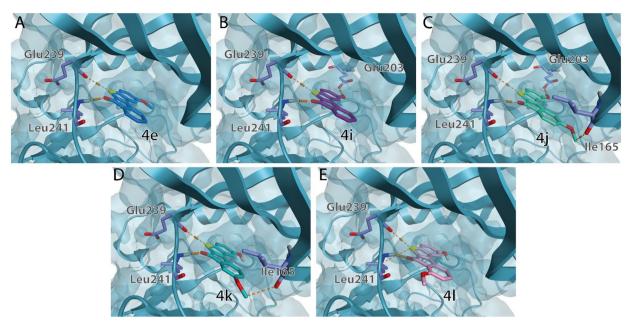


Fig. 4 Top docking poses obtained for the 5 most potent hits 4e, i, j, k, l, (A, B, C, D and E respectively), obtained from the study with the X-ray structure of DYRK1A (PDB: 5AIK). Stabilizing interactions are highlighted in orange. Compounds 4a-m representations are available in ESI† (Fig. S3).

of the structures bearing a hydroxyl group on the benzothiophene moiety, more interactions can be observed with Glu203 (4i and 4j, Fig. 4B and C). Depending on the position of a methoxy group on the indenone ring, another weak interaction can occasionally be detected with Ile165, as observed with compounds 4j and 4k

(Fig. 4C and D). Surprisingly, the most active compound 4k did not show any interaction between the phenol group and Glu203.

Additionally, the best hit 4k was overlaid with known ligands from the literature (harmine, INDY and compound 3a (R' = OH)) in order to better understand its position in the protein pocket (Fig. 5). The consistency on the heteroatoms'

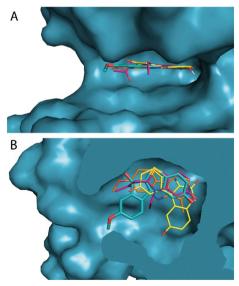


Fig. 5 Superposition of reference ligands described in the literature with compound 4k. These images are generated from the docking of the molecules with the X-ray structure of DYRK1A (PDB: 5AIK), whose surface is represented in dark blue. Compound 4k is depicted with thick sticks in turquoise, harmine in orange, INDY in magenta and compound 3a (R' = OH) in yellow (A: side view of the ATP cleft. B: Top view).

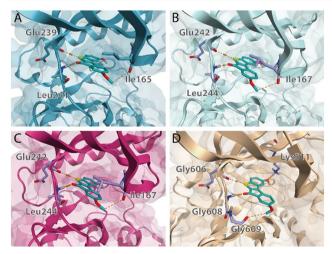


Fig. 6 Top docking poses of compound 4k within the X-ray structures of DYRK1A (PDB: 5AIK) in dark blue (A), CLK1 (PDB: 6RAA) in cyan-grey (B), CLK4 (PDB: 6FYV) in magenta (C) and haspin (PDB: 3IQ7) in wheat (D). The kinases are shown as ribbon with their surfaces in transparency. The results showed marked homology in the stabilization of compound 4k within the 4 proteins. Residues engaged in stabilizing interactions are highlighted in orange. Haspin kinase exhibits a slightly different binding system.

positions showed a similarity in the fitting mode in the protein pocket.

As mentioned above, the most potent compound 4k showed crossed inhibition with three off-target kinases: CLK1, CLK4 and haspin. In order to evaluate similarities of the ligand/protein interactions, compound 4k was docked within the four protein X-ray structures (Fig. 6). Some homologies in the binding mode were established. The H-bond interaction observed with Leu241 in DYRK1A (Fig. 6A) can also be shown with Leu244 in CLK1 (Fig. 6B) and CLK4 (Fig. 6C), and a similar H-bond is present with Gly608 in haspin (Fig. 6D). The sulfur atom sigma* interaction with Glu239 in DYRK1A can also be shown with Glu242 in CLK1 and CLK4, respectively, and with Glu606 for haspin. A similar weak interaction as Ile165 in DYRK1A can also be observed with Leu167 in CLK1 and CLK4. In haspin, two more interactions were identified: 1) a weak interaction of Gly609 with the methoxy group on the indanone side, 2) a H-bond between Lys511 and the hydroxyl group of 4k. The latter could be explained by the smaller distance between Lys188 amino group and 4k phenol moiety (Fig. 6D).

Conclusion

Research Article

The goal of this study was to modulate the structure of known DYRK1A inhibitors with marked modifications, i.e. a ring contraction and an isosteric NH to S modification, thus leading to original 6*H*-benzo[*b*]indeno[1,2-*d*]thiophen-6-ones 4.

Our pharmacomodulation study also aimed at exploring the molecular diversity on this scaffold: this was achieved by investigating the influence of grafting different moieties such as methoxy/hydroxy/fluorine substitution onto the benzothiophene ring and the presence of a methoxy group on different positions of the indanone part of tetracyclic derivatives 4a-m.

First designed as a DYRK1A inhibitor, the most active compound 4k of this series proved to be a potent multiple CLK1/CLK4/DYRK1A/haspin inhibitor, with interesting IC50 values (20/26/35/76 nM, respectively). Such a cross inhibition was already reported in the literature for DYRK1A inhibitors but was quite surprising, regarding the pronounced structural modifications, compared to the parent scaffolds.

The antiproliferative effects of the most active compound 4k were also evaluated on two different glioblastoma cell lines. Surprisingly and given the broad inhibitory profile of this compound, the observed impact was only moderate.

The docking study of the entire set of molecules 4a-m on DYRK1A crystal structure has provided a very interesting insight into the ligands-protein interactions of the most active derivatives 4e, i-l, demonstrating key interactions between the benzo[b]thiophene ring sulfur atom and the indenone oxygen atom with residues Glu242 and Leu244 respectively. Comparison of docking poses of the most active DYRK1A inhibitor 4k with CLK1, CLK4 and haspin showed similarities of protein ligand interactions for DYRK1A, CLK1

and CLK4 whereas interactions within the haspin ATP pocket relied on different residues.

Lastly, as a preliminary approach to evaluate the druggability of these tetracyclic derivatives, microsomal stability studies have shown the fast degradation of the most active compound 4k, thus impeding its further development in its present form. To overcome this issue, a carbamate⁷⁸ prodrug of the phenol group^{79,80} is currently under investigation to increase compound half-life, which could also be relevant for enhancing blood-brain barrier crossing⁸¹ or compound targeting,⁸²⁻⁸⁵ before considering further in vivo studies.

Experimental section

Chemistry - general

All moisture/air-sensitive reactions were carried out under a positive pressure of argon and with oven-dried glassware. Melting points were measured on a Büchi B-540 melting point apparatus and are uncorrected. Infra-red spectra (IR) were recorded on a Perkin Elmer Spectrum Two apparatus, equipped with an attenuated total reflectance sampling module: absorption bands are reported in cm⁻¹. Proton nuclear magnetic resonance (1H NMR) and carbon nuclear magnetic resonance (13C NMR) spectra were recorded on Bruker DRX400 and AV500 Fourier transform spectrometers, using an internal deuterium lock, operating at 400 or 500 MHz. Chemical shifts are reported in parts per million (ppm) relative to internal standards (tetramethylsilane, $\delta_{\rm H}$ = $\delta_{\rm C}$ = 0.00; CDCl₃, $\delta_{\rm H}$ = 7.26 and $\delta_{\rm C}$ = 77.16; DMSO- $d_{\rm 6}$, $\delta_{\rm H}$ = 2.50 and $\delta_{\rm C}$ = 39.52; acetone- d_6 , $\delta_{\rm H}$ = 2.05 and $\delta_{\rm C}$ = 29.84). Be Data are presented as follows: chemical shift (δ , ppm), multiplicity (s = singlet, d = doublet t = triplet, q = quadruplet, <math>dd =doublet of doublet, m = multiplet, br = broad), coupling constant, integration. Atom numbering refers to benzo[b] thiophene or aromatic compounds nomenclature.

Agilent UHPLC/MS consists of a 1290 Infinity system with a binary pump, degasser, autosampler, thermostated column compartment, 1260 diode array detector and 6120 single quadrupole mass spectrometer. The entire system was controlled by Chemstation software (Agilent Technologies). The column was an Agilent Poroshell 120 SB-C18, 2.7 µm, 2.1 × 50 mm. The samples were analysed in the positive ion mode of the electro spray ionisation (ESI) source, whose conditions were as follow: gas temperature, 350 °C, drying gas at 12.0 l min⁻¹, nebulizer gas at 35 psig, V_{cap} at 3000 V, fragmentor at 60 V.

High-resolution mass spectra were recorded on a Bruker QTOF Impact II mass spectrometer (ESI mode).

Reactions were monitored with analytical thin layer chromatography (TLC), which was carried out using Merck commercial aluminium sheets coated (0.2 mm layer thickness) with Kieselgel 60 F₂₅₄, with visualization by ultraviolet and acidic anisaldehyde staining solution. Proportions of solvents used for TLC are by volume. Product purification by flash column chromatography was performed using Merck Kieselgel 60 Å (40-63 mm) or using pre-packed silica gel columns.

Proportions of solvents used for column chromatography are by Tetrahydrofuran (THF), N,N-dimethylformamide (DMF), dimethylsulfoxide (DMSO) (Acroseal®, over molecular sieves) were purchased from Acros Organics. For extraction/ purification, diethyl ether, dichloromethane (DCM), cyclohexane and ethyl acetate (AcOEt) were of reagent grade. All other chemical reagents were used as received. Commercial n-BuLi solutions in hexanes were titrated using N-benzylbenzamide.87

9a, 38,39 5-Methoxybenzo[*b*]thiophene 5-fluorobenzo[b] thiophene 9b, 40,41 (benzo[b]thiophen-5-yloxy)-tert-butyl-dimethylsilane 9c, 42,43 (2-iodo-3-methoxyphenyl)methanol 13b, 46 (2-iodo-4methoxyphenyl) methanol 13c,88 (2-iodo-6-methoxyphenyl) methanol 13e45 and 2-iodo-5-methoxybenzaldehyde 8d44 were prepared according to literature procedures.

Synthetic procedures

Preparation of aldehydes 8a-c,e⁴⁵. The 2-iodobenzyl alcohol was dissolved in dichloromethane (0.2 M) with silica gel (1 g mmol⁻¹). The slurry was stirred at rt followed by the addition of PDC (2 equiv.). The reaction was stirred until the starting material was consumed by TLC typically 6 h. The crude was filtered through a silica gel pad, washing with ethyl acetate. The crude aldehyde was purified if required by flash column chromatography using ethyl acetate and cyclohexane.

2-Iodobenzaldehyde 8a. Scale: 2-iodobenzylic alcohol 13a (0.998 g, 4.27 mmol), silica (4.285 g), PDC (3.232 g, 8.60 mmol). Compound 8a (0.973 g, 98%) was obtained as a pale yellow solid and was used without further purification.

Spectral data were identical to those reported in the literature.89

2-Iodo-3-methoxybenzaldehyde 8b. Scale: (2-iodo-3methoxyphenyl)methanol 13b (1.423 g, 5.39 mmol), silica (5.400 g), PDC (4.063 g, 10.80 mmol). The residue was purified by flash chromatography (20% of EtOAc in cyclohexane) to afford compound 8b as a white solid (1.070 g, 76%).

Spectral data were identical to those reported in the literature.90

2-Iodo-4-methoxybenzaldehyde (2-iodo-4-8c. Scale: methoxyphenyl) methanol 13c (1.711 g, 6.48 mmol), silica (6.520 g), PDC (4.879 g, 12.97 mmol). The residue was purified by flash chromatography (20% of EtOAc in cyclohexane) to afford compound 8c as a white solid (1.512 g, 89%).

Spectral data were identical to those reported in the literature.91

2-Iodo-6-methoxybenzaldehyde (2-iodo-6-8e. Scale: methoxyphenyl) methanol 13e (1.240 g, 4.70 mmol), silica (4.200 g), PDC (3.136 g, 8.34 mmol). The residue was purified by flash chromatography (20% of EtOAc in cyclohexane) to afford compound 8e as a white solid (0.750 g, 61%).

Spectral data were identical to those reported in the literature.45

General procedure A for the preparation of alcohols 7 using *n*-butyl lithium 2-deprotonation of benzo[b]thiophene 9 and subsequent electrophile addition of ortho-iodoaldehydes 8. To a solution of benzo[b]thiophene 9 (1.60 mmol) in THF (5 mL) under an argon atmosphere at - 78 °C was added dropwise n-BuLi 2.5 M in hexanes (0.72 mL, 1.80 mmol). The mixture was stirred at -78 °C for 1 h. A solution of 2-iodobenzaldehyde 8 (1.95 mmol) in THF (7 mL) was added then added dropwise. The stirring of the mixture was continued at - 78 °C for 1 h and at room temperature for 4 h. Subsequently, the mixture was quenched with brine (20 mL) and ethyl acetate (20 mL) was then added. After decantation, the aqueous layer was extracted with ethyl acetate (2 × 20 mL). The combined organic layers were washed with brine (3 × 20 mL) and dried over Na₂SO₄, filtered and concentrated under reduced pressure to give a brown residue. The crude product was purified by flash chromatography (gradient of EtOAc in cyclohexane) to afford the desired alcohol 7.

Benzo[b]thiophen-2-yl(2-iodo-3-methoxy phenyl)methanol 7a. According to general procedure A, scale: benzo[b]thiophene (0.205 g, 1.53 mmol), n-BuLi 2.5 M in hexanes (0.72 mL, 1.80 mmol), 2-iodo-3-methoxybenzaldehyde (0.515 g, 1.96 mmol). The residue was purified by flash chromatography (0 to 30% of EtOAc in cyclohexane) to afford compound 7a as a white solid (0.452 g, 75%), m.p. 48.0-49.2 °C. IR: 3532, 3357, 3057, 3002, 2962, 2936, 2835, 2329, 1699, 1585, 1566, 1463, 1425, 1365, 1333, 1262, 1184, 1155, 1105, 1088, 1068, 1009, 936, 893, 859, 834, 793, 767, 745, 725, 668, 657, 590, 553, 480. ¹H NMR (400 MHz, acetone- d_6) $\delta = 7.86-7.81$ (m, 1H), 7.75-7.71 (m, 1H), 7.43-7.37 (m, 2H), 7.33-7.26 (m, 2H), 7.18 (s, 1H), 6.95 (dd, J = 7.1, 2.4 Hz, 1H), 6.45 (dd, J = 4.6, 1.1 Hz, 1H), 5.52 (d, J = 4.6 Hz, 1H), 3.90 (s, 3H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 158.68(C)$, 149.82(C), 148.68(C), 140.61(C), 140.47(C), 130.34(CH), 124.97(CH), 124.90(CH), 124.32(CH), 123.05(CH), 122.15(CH), 121.17(CH), 111.16(CH), 90.97(C), 76.45(CH), 56.92(CH₃). LC/MS (retention time 4.21 min) m/z(ESI⁺) 379.00 (MH⁺-H₂O, 100%), 418.90 (MNa⁺, 20.7%). HRMS (ESI⁺): m/z calcd for $C_{16}H_{12}IOS^{+}$ [MH⁺-H₂O]: 378.9648; found: 378.9648.

Benzo[b]thiophen-2-yl(2-iodo-4-methoxy phenyl)methanol 7b. According to general procedure A, scale: benzo[b]thiophene (0.203 g, 1.51 mmol), n-BuLi 2.5 M in hexanes (0.72 mL, 1.80 mmol), 2-iodo-4-methoxybenzaldehyde (0.517 g, 1.97 mmol). The residue was purified by flash chromatography (0 to 30% of EtOAc in cyclohexane) to afford compound 7b as a yellow oil (0.442 g, 74%). IR: 3376, 3055, 3002, 2959, 2936, 2894, 2834, 1702, 1594, 1562, 1484, 1457, 1436, 1395, 1363, 1305, 1282, 1228, 1179, 1154, 117, 1091, 1065, 1026, 1015, 938, 852, 343, 784, 745, 726, 708, 667, 591, 552, 529, 482. ¹H NMR (400 MHz, acetone- d_6) δ = 7.84 (ddt, J = 7.0, 1.6, 0.9 Hz, 1H), 7.77– 7.71 (m, 1H), 7.63 (d, J = 8.8 Hz, 1H), 7.41 (d, J = 2.6 Hz, 1H), 7.34–7.26 (m, 2H), 7.17 (t, J = 1.0 Hz, 1H), 7.07 (dd, J = 8.7, 2.6 Hz, 1H), 6.25 (d, J = 4.5 Hz, 1H), 5.46 (d, J = 4.5 Hz, 1H), 3.82 (s, 3H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 160.49$ (C), 150.40(C), 140.66(C), 140.58(C), 139.01(C), 129.47(CH), 125.03(CH), 124.92(CH), 124.75(CH), 124.36(CH), 123.08(CH), 121.93(CH), 115.60(CH), 98.40(C), 75.82(CH), 55.95(CH₃). LC/ MS (retention time 4.38 min) m/z (ESI⁺) 379.00 (MH⁺-H₂O, 100%), 418.90 (MNa⁺, 17.5%). HRMS (ESI⁺): m/z calcd for C₁₆- $H_{12}IOS^{+}$ [MH⁺-H₂O]: 378.9648; found: 378.9644.

Benzo[b]thiophen-2-yl(2-iodo-5-methoxy phenyl)methanol 7c. According to general procedure A, scale: benzo[b]thiophene (0.205 g, 1.53 mmol), n-BuLi 2.5 M in hexanes (0.72 mL, 1.80 mmol), 2-iodo-4-methoxybenzaldehyde (0.511 g, 1.95 mmol). The residue was purified by flash chromatography (0 to 30% of EtOAc in cyclohexane) to afford compound 7c as an orange oil (0.410 g, 68%). IR: 3443, 3073, 3049, 2959, 2931, 2850, 2831, 1590, 1564, 1458, 1437, 1411, 1397, 1281, 1271, 1224, 1156, 1115, 1052, 1024, 1001, 929, 881, 865, 836, 808, 791, 745, 726, 666, 633, 588, 556, 518, 457. ¹H NMR (400 MHz, acetone- d_6) $\delta = 7.85$ (dd, J = 6.4, 2.1 Hz, 1H), 7.75 (dd, J = 8.8, 3.0 Hz, 2H), 7.39 (d, J = 3.1 Hz, 1H), 7.34–7.22 (m, 2H), 7.19 (s, 1H), 6.75 (dd, J = 8.7, 3.1 Hz, 1H), 6.23 (d, J = 4.5 Hz, 1H), 5.56 (d, J = 4.6 Hz, 1H), 3.81 (s, 3H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 161.43(C)$, 149.44(C), 147.90(C), 140.70(C), 140.66(CH), 140.49(C), 125.06(CH), 125.03(CH), 124.44(CH), 123.10(CH), 122.40(CH), 116.69(CH), 114.78(CH), 86.42(C), 76.09(CH), 55.77(CH₃). LC/MS (retention time 4.38 min) m/z (ESI⁺) 379.00 (MH⁺-H₂O, 100%), 418.90 (MNa⁺, 10.8%). HRMS (ESI⁺): m/z calcd for $C_{16}H_{12}IOS^{+}$ [MH⁺-H₂O]: 378.9648; found: 378.9645.

Benzo[b]thiophen-2-yl(2-iodo-6-methoxy phenyl)methanol 7d. According to general procedure A, scale: benzo[b]thiophene (0.137 g, 1.02 mmol), n-BuLi 2.5 M in hexanes (0.48 mL, 1.20 mmol), 2-iodo-6-methoxybenzaldehyde (0.340 g, 1.30 mmol). The residue was purified by flash chromatography (0 to 100% of MeOH in H2O, using a reversed phase C18 column) to afford compound 7d as a white solid (0.153 g, 38%), m.p. 109.8-110.7 °C. IR: 3529, 3095, 3059, 3043, 3013, 2970, 2940, 2922, 2853, 2839, 1582, 1566, 1458, 1432, 1404, 1324, 1296, 1262, 1231, 1194, 1176, 1154, 1140, 1098, 1083, 1011, 935, 889, 862, 845, 831, 788, 772, 744, 728, 706, 677, 657, 585, 556, 506, 462. ¹H NMR (400 MHz, acetone- d_6) δ 7.87–7.83 (m, 1H), 7.71 (dd, J = 6.7, 2.1 Hz, 1H), 7.57 (dd, J = 7.7, 1.2 Hz, 1H), 7.30 (ddd, J = 7.2, 5.2, 1.6 Hz, 2H), 7.13 (dd, J = 16.4, 7.6 Hz, 2H), 7.02 (s, 1H), 6.42–6.36 (m, 1H), 5.09 (d, J = 10.7 Hz, 1H), 3.82 (s, 3H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 158.95$ (C), 150.19(C), 140.85(C), 140.54(C), 133.71(C), 133.09(CH), 131.67(CH), 124.97(CH), 124.69(CH), 124.15(CH), 123.00(CH), 120.59(CH), 113.39(CH), 99.89(C), 77.99(CH), 56.35(CH₃). LC/ MS (retention time 4.52 min) m/z (ESI⁺) 379.00 (MH⁺-H₂O, 100%), 419.00 (MNa⁺, 16.6%). HRMS (ESI⁺): m/z calcd for C₁₆- $H_{12}IOS^{+}$ [MH⁺-H₂O]: 378.9648; found: 378.9643.

(2-Iodophenyl)(5-methoxy benzo[b]thiophen-2-yl)methanol 7e. According to general procedure A, scale: 5-methoxy benzo[b] thiophene (0.246 g, 1.50 mmol), n-BuLi 2.5 M in hexanes (0.72 mL, 1.80 mmol), 2-iodobenzaldehyde (0.454 g, 1.96 mmol). The residue was purified by flash chromatography (0 to 30% of EtOAc in cyclohexane) to afford compound 7e as a yellow oil (0.523 g, 88%). IR: 3527, 3387, 3059, 2999, 2948, 2935, 2902, 2830, 1700, 1600, 1584, 1533, 1456, 1434, 1363, 1331, 1298, 1279, 1216, 1151, 1113, 1069, 1047, 1021, 1007, 943, 855, 832, 802, 746, 730, 718, 668, 649, 619, 597, 561, 537, 492. ¹H NMR (400 MHz, acetone- d_6) $\delta = 7.88$ (dd, J = 7.9, 1.1 Hz, 1H), 7.79 (dd, J = 7.8, 1.7 Hz, 1H), 7.70 (d, J = 8.8 Hz, 1H), 7.51-7.45 (m, 1H), 7.27 (d, J = 2.5 Hz, 1H), 7.12 (s, 1H), 7.08

(td, J = 7.6, 1.7 Hz, 1H), 6.94 (dd, J = 8.8, 2.5 Hz, 1H), 6.30 (d, J = 8.8, 2.5 Hz, 1H), 6J = 4.3 Hz, 1H), 5.56 (d, J = 4.5 Hz, 1H), 3.81 (s, 3H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 158.47(C)$, 150.75(C), 146.84(C), 141.52(C), 140.03(CH), 132.82(C), 130.44(CH), 129.47(CH), 129.00(CH), 123.68(CH), 122.22(CH), 115.12(CH), 106.53(CH), 98.37(C), 76.25(CH), 55.66(CH₃). LC/MS (retention time 4.28 min) m/z (ESI⁺) 379.00 (MH⁺-H₂O, 100%), 418.90 (MNa⁺, 15.5%). HRMS (ESI⁺): m/z calcd for $C_{16}H_{12}IOS^{+}$ [MH⁺-H₂O]: 378.9648; found: 378.9646.

(2-Iodo-3-methoxyphenyl)(5-methoxy benzo[b]thiophen-2-yl) methanol 7f. According to general procedure A, scale: 5-methoxybenzo[b]thiophene (0.252 g, 1.53 mmol), n-BuLi 2.5 M in hexanes (0.72 mL, 1.80 mmol), 2-iodo-3-methoxybenzaldehyde (0.519 g, 1.98 mmol). The residue was purified by flash chromatography (0 to 30% of EtOAc in cyclohexane) to afford compound 7f as a white solid (0.392 g, 60%), m.p. 133.0-135.4 °C. IR: 3566, 3530, 3068, 3000, 2970, 2934, 2905, 2834, 1584, 1598, 1564, 1526, 1455, 1428, 1357, 1332, 1284, 1276, 1264, 1246, 1211, 1173, 1116, 1068, 1010, 939, 859, 821, 794, 765, 725, 669, 679, 627, 583. ¹H NMR (400 MHz, acetone- d_6) $\delta = 7.69$ (d, J = 8.8Hz, 1H), 7.43-7.36 (m, 2H), 7.26 (d, J = 2.4 Hz, 1H), 7.09 (s, 1H), 6.97-6.90 (m, 2H), 6.42 (dd, J = 4.7, 1.1 Hz, 1H), 5.48 (d, J = 4.6Hz, 1H), 3.90 (s, 3H), 3.81 (s, 3H). ¹³C NMR (101 MHz, acetone d_6) $\delta = 158.67(C)$, 158.50(C), 150.99(C), 148.75(C), 141.57(C), 132.83(C), 130.31(CH), 123.66(CH), 122.14(CH), 121.18(CH), 115.06(CH), 111.14(CH), 106.52(CH), 90.98(C), 76.50(CH), $56.93(CH_3)$, $55.68(CH_3)$. LC/MS (retention time 4.15 min) m/z(ESI⁺) 409.00 (MH⁺-H₂O, 100%), 449.00 (MNa⁺, 30.0%). HRMS (ESI⁺): m/z calcd for $C_{17}H_{14}IO_2S^+$ [MH⁺-H₂O]: 408.9754; found: 408.9752.

(2-Iodo-4-methoxyphenyl)(5-methoxybenzo[b]thiophen-2-yl) methanol 7g. According to general procedure A, scale: 5-methoxybenzo[b]thiophene (0.210 g, 1.28 mmol), n-BuLi 2.5 M in hexanes (0.60 mL, 1.50 mmol), 2-iodo-4-methoxybenzaldehyde (0.428 g, 1.63 mmol). The residue was purified by flash chromatography (0 to 30% of EtOAc in cyclohexane) to afford compound 7g as a yellow oil (0.447 g, 82%). IR: 3389, 3062, 3000, 2956, 2936, 2899, 2833, 1703, 1595, 1563, 1534, 1484, 1456, 1436, 1363, 1330, 1281, 1219, 1180, 1151, 1070, 1029, 943, 850, 803, 730, 718, 893, 657, 595, 563, 530. 1 H NMR (400 MHz, acetone- d_6) δ = 7.69 (d, J = 8.8 Hz, 1H), 7.62 (d, J = 8.7 Hz, 1H), 7.41 (d, J = 2.6 Hz, 1H), 7.27 (d, J = 2.5 Hz, 1H), 7.09–7.04 (m, 2H), 6.93 (dd, J =8.8, 2.5 Hz, 1H), 6.22 (d, J = 4.4 Hz, 1H), 5.42 (d, J = 4.5 Hz, 1H), 3.82 (s, 3H), 3.82 (s, 3H). 13 C NMR (101 MHz, acetone- d_6) $\delta =$ 160.45(C), 158.55(C), 151.56(C), 141.66(C), 139.07(C), 132.85(C), 129.45(CH), 124.71(CH), 123.70(CH), 121.90(CH), 115.56(CH), 115.05(CH), 106.55(CH), 98.39(C), 75.85(CH), 55.94(CH₃), 55.69(CH₃). LC/MS (retention time 4.30 min) m/z (ESI⁺) 409.00 $(MH^+-H_2O, 100\%), 449.00 (MNa^+, 23.4\%)$. HRMS (ESI⁺): m/z calcd for $C_{17}H_{14}IO_2S^+$ [MH⁺-H₂O]: 408.9754; found: 408.9749.

(2-Iodo-5-methoxyphenyl)(5-methoxy benzo[b]thiophen-2-yl) methanol 7h. According to general procedure A, scale: 5-methoxybenzo[b]thiophene (0.247 g, 1.50 mmol), n-BuLi 2.5 M in hexanes (0.72 mL, 1.80 mmol), 2-iodo-5-methoxybenzaldehyde (0.510 g, 1.95 mmol). The residue was purified by flash chromatography (0 to 30% of EtOAc in cyclohexane) to afford

compound 7h as a yellow oil (0.582 g, 91%). IR: 3428, 3062, 3001, 2973, 2935, 2910, 2883, 2832, 1599, 1584, 1564, 1532, 1456, 1447, 1406, 1370, 1331, 1294, 1278, 1263, 1240, 1204, 1150, 1137, 1111, 1069, 1045, 1019, 997, 943, 935, 924, 890, 859, 811, 802, 778, 756, 721, 697, 664, 631, 621, 590, 568, 521, 454. ¹H NMR (400 MHz, acetone- d_6) $\delta = 7.74$ (d, J = 8.7 Hz, 1H), 7.70 (d, J = 8.8 Hz, 1H), 7.38 (d, J = 3.1 Hz, 1H), 7.28 (d, J = 2.5 Hz, 1H), 7.11 (s, 1H), 6.94 (dd, J = 8.8, 2.5 Hz, 1H), 6.74 (dd, J = 8.7, 3.1 Hz, 1H), 6.21 (d, J =4.1 Hz, 1H), 5.53 (d, J = 4.6 Hz, 1H), 3.82 (s, 3H), 3.81 (s, 3H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 161.42(C)$, 158.57(C), 150.61(C), 147.97(C), 141.58(C), 140.62(CH), 132.90(C), 123.72(CH), 122.38(CH), 116.66(CH), 115.21(CH), 114.77(CH), 106.60(CH), 86.43(C), 76.13(CH), 55.77 (CH₃), 55.69(CH₃). LC/MS (retention time 4.31 min) m/z (ESI⁺) 409.00 (MH⁺-H₂O, 100%), 449.00 $(MNa^+, 32.4\%), 450.10 (7.8), 451.00 (2.6).$ HRMS $(ESI^+): m/z$ calcd for $C_{17}H_{14}IO_2S^+$ [MH⁺-H₂O]: 408.9754; found: 408.9751.

(5-((Tert-Butyldimethylsilyl)oxy)benzo[b]thiophen-2-yl)(2-iodophenyl) methanol 7i. According to general procedure A, scale: (benzo[b] thiophen-5-yloxy)(tert-butyl)dimethylsilane (0.400 g, 1.51 mmol), n-BuLi 2.5 M in hexanes (0.72 mL, 1.80 mmol), 2-iodobenzaldehyde (0.452 g, 1.95 mmol). The residue was purified by flash chromatography (0 to 30% of EtOAc in cyclohexane) to afford compound 7i as a yellow oil (0.481 g, 64%). IR: 3436, 3054, 2962, 2929, 2880, 2858, 1594, 1566, 1535, 1463, 1444, 1390, 1364, 1342, 1311, 1288, 1257, 1207, 1143, 1113, 1092, 1066, 1049, 1008, 959, 939, 870, 853, 835, 811, 784, 745, 730, 720, 701, 680, 676, 659, 637, 623, 605, 590, 560, 543, 485. ¹H NMR (400 MHz, acetone- d_6) δ = 7.88 (dd, J = 7.9, 1.1 Hz, 1H), 7.77 (dd, J = 7.8, 1.7 Hz, 1H), 7.70 (d, J = 8.6 Hz, 1H), 7.48 (td, J = 7.5, 1.0 Hz, 1H), 7.25 (d, J = 2.3 Hz, 1.0 Hz, 1.0 Hz)1H), 7.11-7.07 (m, 2H), 6.90 (dd, J = 8.6, 2.4 Hz, 1H), 6.27 (d, J = 4.5Hz, 1H), 5.53 (d, J = 4.5 Hz, 1H), 1.00 (s, 9H), 0.22 (s, 6H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 153.96$ (C), 150.94(C), 146.92(C), 141.81(C), 140.10(CH), 133.83(C), 130.51(CH), 129.54(CH), 129.09(CH), 123.76(CH), 122.02(CH), 119.32(CH), 114.35(CH), 98.36(C), 76.32(CH), 26.07(CH₃), 18.79(C), -4.32(CH₃). LC/MS (retention time 5.89 min) m/z (ESI⁺) 479.10 (MH⁺-H₂O, 100%). HRMS (ESI⁺): m/z calcd for $C_{21}H_{24}IOSSi^+$ [MH⁺-H₂O]: 479.0356; found: 479.0347.

(5-((Tert-Butyldimethylsilyl)oxy)benzo[b]thiophen-2-yl)(2-iodo-4-methoxyphenyl)methanol 7j. According to general procedure A, scale: (benzo[b]thiophen-5-yloxy)(tert-butyl)dimethylsilane (0.322 g, 1.22 mmol), n-BuLi 2.5 M in hexanes (0.60 mL, 1.50 mmol), 2-iodo-4-methoxybenzaldehyde (0.421 g, 1.60 mmol). The residue was purified by flash chromatography (0 to 30% of EtOAc in cyclohexane) to afford compound 7j as a yellow oil (0.581 g, 91%). IR: 3386, 2954, 2929, 2893, 2856, 1705, 1595, 1563, 1531, 1486, 1471, 1462, 1445, 1390, 1361, 1313, 1282, 1254, 1226, 1181, 1151, 1093, 1068, 1027, 1013, 967, 939, 855, 837, 800, 779, 737, 720, 674, 591, 563. ¹H NMR (400 MHz, acetone- d_6) δ = 7.69 (d, J = 8.6 Hz, 1H), 7.62 (d, J = 8.7 Hz, 1H), 7.41 (d, J = 2.6 Hz, 1H), 7.24 (d, J = 2.3 Hz, 1H), 7.09–7.04 (m, 2H), 6.89 (dd, J = 8.6, 2.4 Hz, 1H), 6.22 (d, J =4.4 Hz, 1H), 5.41 (d, J = 4.5 Hz, 1H), 3.82 (s, 3H), 1.00 (s, 9H), 0.22 (s, 6H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 160.47$ (C), 151.68(C), 141.88(C), 139.05(C), 133.82(C), 129.48(CH), 124.71(CH), 123.74(CH), 121.68(CH), 119.22(CH),

115.60(CH), 114.31(CH), 98.39(C), 75.87(CH), 55.95(CH₃), 26.07(CH₃), 18.79 (C), -4.31 (CH₃). LC/MS (retention time 5.86 min) m/z (ESI⁺) 509.10 (MH⁺-H₂O, 100%). HRMS (ESI⁺): m/z calcd for $C_{22}H_{26}IO_2SSI^+$ [MH⁺-H₂O]: 509.0462; found: 509.0461.

(5-((Tert-Butyldimethylsilyl)oxy)benzo[b]thiophen-2-yl)(2-iodo-5-methoxyphenyl)methanol 7k. According to general procedure A, scale: (benzo[b]thiophen-5-yloxy)(tert-butyl)dimethylsilane (0.404 g, 1.52 mmol), n-BuLi 2.5 M in hexanes (0.72 mL, 1.80 mmol), 2-iodo-5-methoxybenzaldehyde (0.513 g, 1.95 mmol). The residue was purified by flash chromatography (0 to 30% of EtOAc in cyclohexane) to afford compound 7k as a yellow oil (0.434 g, 54%). IR: 3418, 3054, 3002, 2954, 2928, 2884, 2856, 1704, 1595, 1567, 1532, 1463, 1445, 1414, 1362, 1312, 1287, 1255, 1226, 1148, 1114, 1068, 1047, 1034, 1003, 967, 939, 873, 837, 804, 780, 740, 720, 677, 635, 587, 521, 486. ¹H NMR (400 MHz, acetone- d_6) $\delta = 7.74$ (d, J = 8.7 Hz, 1H), 7.70 (d, J = 8.6 Hz, 1H), 7.38 (d, J = 3.1 Hz, 1H), 7.25 (d, J = 2.3 Hz, 1Hz)1H), 7.09 (s, 1H), 6.90 (dd, J = 8.6, 2.4 Hz, 1H), 6.74 (dd, J =8.7, 3.2 Hz, 1H), 6.20 (dd, J = 4.6, 1.2 Hz, 1H), 5.52 (d, J = 4.6Hz, 1H), 3.81 (s, 3H), 1.00 (s, 9H), 0.22 (s, 6H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 161.42(C)$, 153.96(C), 150.70(C), 147.93(C), 141.80(C), 140.62(CH), 133.85(C), 123.77(CH), 122.15(CH), 119.35(CH), 116.66(CH), 114.79(CH), 114.37(CH), 86.42(C), 76.14(CH), 55.77(CH₃), 26.07(CH₃), 18.79 (C), -4.31 (CH₃). LC/MS (retention time 5.87 min) m/z (ESI⁺) 509.10 $(MH^+-H_2O, 100\%), 549.10 (MNa^+, 6.3\%). HRMS (ESI^+): m/z$ calcd for $C_{22}H_{26}IO_2SSi^+$ [MH⁺-H₂O]: 509.0462; found: 509.0462.

(5-((Tert-Butyldimethylsilyl)oxy)benzo[b]thiophen-2-yl)(2-iodo-6-methoxyphenyl)methanol 7l. According to general procedure A, scale: (benzo[b]thiophen-5-yloxy)(tert-butyl)dimethylsilane (0.271 g, 1.03 mmol), n-BuLi 2.5 M in hexanes (0.45 mL, 1.13 mmol), 2-iodo-6-methoxybenzaldehyde (0.343 g, 1.31 mmol). The residue was purified by flash chromatography (0 to 100% of MeOH in H₂O, using a reversed phase C18 column) afford compound 7l as a white solid (0.110 g, 20%), m.p. 124.6-125.6 °C. IR: 3533, 3097, 3054, 3008, 2958, 2917, 2852, 1595, 1567, 1535, 1445, 1432, 1408, 1362, 1326, 1310, 1290, 1256, 1219, 1176, 1153, 1139, 1099, 1082, 1068, 1012, 965, 938, 867, 832, 818, 787, 760, 735, 729, 713, 678, 659, 636, 613, 588, 563, 538, 512, 459. ¹H NMR (400 MHz, acetone- d_6) $\delta = 7.69$ (d, J =8.6 Hz, 1H), 7.57 (dd, J = 7.7, 1.3 Hz, 1H), 7.21 (d, J = 2.3 Hz, 1H), 7.15 (dd, J = 8.3, 1.2 Hz, 1H), 7.11 (d, J = 7.7 Hz, 1H), 6.92 (dd, J = 1.3, 0.6 Hz, 1H), 6.88 (dd, J = 8.6, 2.4 Hz, 1H), 6.34 (s, 1H), 5.05 (s, 1H), 3.83 (s, 3H), 1.00 (s, 9H), 0.22 (s, 6H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 158.97$ (C), 153.92(C), 151.46(C), 142.17(C), 133.73(C), 133.71(C), 133.11(CH), 131.65(CH), 123.66(CH), 120.42(CH), 118.97(CH), 114.13(CH), 113.42(CH), 99.90(C), 78.11(CH), 56.38(CH₃), 26.08(CH₃), 18.79 (C), -4.30 (CH₃). LC/MS (retention time 6.03 min) m/z(ESI⁺) 509.10 (MH⁺-H₂O, 100%), 549.10 (MNa⁺, 8.2%). HRMS (ESI⁺): m/z calcd for $C_{22}H_{26}IO_2SSi^+$ [MH⁺-H₂O]: 509.0462; found: 509.0456.

(5-Fluorobenzo[b]thiophen-2-yl)(2-iodo-5-methoxyphenyl)methanol 7m. According to general procedure A, scale: 5-fluoro benzo[b]

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thiophene (0.229 g, 1.50 mmol), n-BuLi 2.5 M in hexanes (0.72 mL, 1.80 mmol), 2-iodo-5-methoxybenzaldehyde (0.511 g, 1.95 mmol). The residue was purified by flash chromatography (0 to 30% of EtOAc in cyclohexane) to afford compound 7m as a yellow oil (0.317 g, 51%). IR: 3385, 3068, 3000, 2959, 2935, 2905, 2835, 1702, 1589, 1567, 1535, 1464, 1442, 1413, 1401, 1286, 1228, 1201, 1163, 1140, 1125, 1043, 1002, 954, 864, 798, 772, 746, 716, 687, 660, 628, 566, 521, 469. ¹H NMR (400 MHz, acetone- d_6) $\delta = 7.87$ (dd, J = 8.8, 4.9 Hz, 1H), 7.75 (d, J = 8.7 Hz, 1H), 7.52 (dd, J = 9.8,2.5 Hz, 1H), 7.37 (d, J = 3.1 Hz, 1H), 7.20 (s, 1H), 7.13 (td, J = 9.0, 2.6 Hz, 1H), 6.76 (dd, J = 8.7, 3.1 Hz, 1H), 6.25-6.21 (m, 1H), 5.63 (d, J = 4.6 Hz, 1H), 3.81 (s, 3H). ¹³C NMR (101 MHz, acetone- d_6) δ = 161.65(C, d, J = 240.4 Hz), 161.46(C), 152.46(C), 147.74(C), 141.62(C, d, J = 10.1 Hz), 140.71(CH), 136.27(C), 124.65(CH, d, J = 9.1 Hz), 122.13(CH, d, J = 4.1 Hz), 116.78(CH), 114.79(CH), 113.51(CH, d, J = 25.3 Hz), 109.72(CH, d, J = 23.2 Hz), 86.37(C), 76.06(CH), 55.78(CH₃). ¹⁹F NMR (376 MHz, acetone- d_6) δ = -120.45. LC/MS (retention time 4.45 min) m/z (ESI⁺⁾ 397.00 $(MH^+-H_2O, 100\%), 437.15 (MNa^+, 5.3\%)$. HRMS (ESI^+) : m/z calcd for $C_{16}H_{11}FIOS^{+}$ [MH⁺-H₂O]: 396.9554; found: 396.9550.

General procedure B for the preparation of ketones 6 by an oxidation reaction of alcohols 7. To a solution of alcohol 7 (0.54 mmol) in ACN (12.5 mL) under an argon atmosphere at room temperature was added MnO₂ (0.142 g, 1.63 mmol) and, after a 2 h stirring at rt, a second portion of MnO2 (0.142 g, 1.63 mmol) was added. After stirring for 4 h at room temperature, the reaction mixture was filtered over a pad of silica gel and washed with ACN (2×30 mL). The combined organic layers were dried over Na2SO4, filtered and concentrated under reduced pressure. The crude product was purified by flash chromatography (0 to 20% gradient of EtOAc in cyclohexane) to afford the desired ketone 6.

Benzo[b]thiophen-2-yl(2-iodo-3-methoxyphenyl)methanone 6a. According to general procedure B, scale: benzo[b]thiophen-2yl(2-iodo-3-methoxyphenyl)methanol 7a (0.229 g, 0.58 mmol) and MnO₂ (0.304 g, 3.50 mmol). The residue was purified by flash chromatography (0 to 20% of EtOAc in cyclohexane) to afford compound 6a as a white solid (0.198 g, 87%), m.p. 121.1-122.3 °C. IR: 3059, 3011, 2943, 2921, 2842, 2328, 1640, 1592, 1562, 1511, 1464, 1417, 1333, 1308, 1262, 1248, 1202, 1184, 1143, 1099, 1049, 1012, 939, 915, 868, 841, 802, 776, 750, 732, 718, 709, 664, 601, 580, 547, 489, 483. ¹H NMR (400 MHz, acetone- d_6) $\delta = 8.06$ (dq, J = 8.3, 0.9 Hz, 1H), 8.00 (dt, J= 8.0, 1.0 Hz, 1H), 7.69 (d, J = 0.8 Hz, 1H), 7.58-7.53 (m, 2H), 7.46 (ddd, J = 8.1, 7.1, 1.0 Hz, 1H), 7.18 (dd, J = 8.3, 1.3 Hz, 1H), 7.10 (dd, J = 7.5, 1.3 Hz, 1H), 3.98 (s, 3H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 191.41(C)$, 159.32(C), 147.21(C), 143.89(C), 143.15(C), 140.13(C), 134.69(CH), 130.77(CH), 128.91(CH), 127.47(CH), 126.15(CH), 123.91(CH), 120.91(CH), 113.01(CH), 84.70(C), 57.09(CH₃). LC/MS (retention time 4.56 min) m/z (ESI⁺) 395.00 (MH⁺, 100%), 416.90 (MNa⁺, 18.8%), 810.90 (2MNa⁺, 21.9%). HRMS (ESI⁺): m/z calcd for $C_{16}H_{12}IO_2S^+$ [MH⁺]: 394.9597; found: 394.9596.

Benzo[b]thiophen-2-yl(2-iodo-4-methoxyphenyl)methanone **6b**. Following general procedure B, scale: benzo[b]thiophen-2yl(2-iodo-4-methoxyphenyl)methanol 7b (0.313 g, 0.79 mmol) and MnO₂ (0.418 g, 4.80 mmol). The residue was purified by flash chromatography (0 to 20% of EtOAc in cyclohexane) to afford compound 6b as a colorless oil (0.272 g, 87%). IR: 3261, 3064, 3062, 3046, 2999, 2961, 2935, 2907, 2886, 2830, 2551, 1635, 1591, 1558, 1517, 1481, 1455, 1433, 1424, 1391, 1336, 1313, 1299, 1286, 1266, 1250, 1223, 1183, 1160, 1149, 1121, 1032, 1021, 952, 883, 871, 849, 815, 791, 760, 748, 726, 691, 660, 622, 572, 555, 522, 478. ¹H NMR (400 MHz, acetone- d_6) $\delta = 8.06$ (dq, J = 8.2, 0.9 Hz, 1H), 8.01 (dt, J = 8.1, 1.1 Hz, 1H), 7.76 (d, J = 0.8 Hz, 1H), 7.59–7.54 (m, 3H), 7.47 (ddd, J = 8.1, 7.1, 1.1 Hz, 1H), 7.15 (dd, J = 8.5, 2.5 Hz, 1H),3.93 (s, 3H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 190.79$ (C), 143.79(C), 143.76(C), 140.13(C), 136.82(C), 134.46(CH), 130.90(CH), 128.79(CH), 127.42(CH), 126.30(CH), 126.12(CH), 123.85(CH), 114.45(CH), 93.69(C), 56.24(CH₃). LC/MS (retention time 4.72 min) m/z (ESI⁺) 395.00 (MH⁺, 100%), 417.00 (MNa⁺, 14.7%), 810.90 (2MNa⁺, 26.7%). HRMS (ESI⁺): m/z calcd for $C_{16}H_{12}IO_2S^+$ [MH⁺]: 394.9597; found: 394.9595.

Benzo[b]thiophen-2-yl(2-iodo-5-methoxyphenyl)methanone 6c. According to general procedure B, scale: benzo[b]thiophen-2yl(2-iodo-5-methoxyphenyl)methanol 7c (0.335 g, 0.84 mmol) and MnO₂ (0.441 g, 5.07 mmol). The residue was purified by flash chromatography (0 to 20% of EtOAc in cyclohexane) to afford compound 6c as a yellow oil (0.302 g, 90%). IR: 3062, 3005, 2937, 2923, 2894, 2850, 2828, 2353, 2328, 1638, 1582, 1567, 1507, 1459, 1426, 1383, 1335, 1321, 1262, 1230, 1172, 1159, 1133, 1100, 1047, 1011, 951, 918, 861, 845, 807, 792, 761, 750, 721, 730, 663, 593, 576, 552, 470. ¹H NMR (400 MHz, acetone- d_6) δ 8.07 (dd, J = 8.3, 0.9 Hz, 1H), 8.02 (d, J =8.1 Hz, 1H), 7.87 (d, J = 8.8 Hz, 1H), 7.77 (d, J = 1.0 Hz, 1H), 7.58 (ddd, J = 8.2, 7.1, 1.2 Hz, 1H), 7.48 (ddd, J = 8.1, 7.1, 1.1 Hz, 1H), 7.18 (d, J = 3.1 Hz, 1H), 6.97 (dd, J = 8.8, 3.1 Hz, 1H), 3.88 (s, 3H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 191.07$ (C), 160.75(C), 145.93(C), 143.96(C), 143.03(C), 141.35(C), 140.18(CH), 135.09(CH), 129.00(CH), 127.58(CH), 126.20(CH), 123.92(CH), 118.86(CH), 114.99(CH), 80.62(C), 56.12(CH₃). LC/MS (retention time 4.75 min) m/z (ESI⁺) 395.00 (MH⁺, 100%), 417.00 (MNa⁺, 20.6%), 810.90 (2MNa⁺, 26.3%). HRMS (ESI⁺): m/z calcd for $C_{16}H_{12}IO_2S^+$ [MH⁺]: 394.9597; found: 394.9594.

Benzo[b]thiophen-2-yl(2-iodo-6-methoxyphenyl)methanone 6d. According to general procedure B, scale: benzo[b]thiophen-2yl(2-iodo-6-methoxyphenyl)methanol 7d (0.115 g, 0.29 mmol) and MnO₂ (0.300 g, 3.45 mmol). The residue was purified by flash chromatography (0 to 20% of EtOAc in cyclohexane) afford compound 6d as a colorless oil (0.110 g, 96%). IR: 3288, 3080, 2964, 2937, 2835, 1927, 1646, 1580, 1562, 1512, 1456, 1425, 1360, 1331, 1281, 1258, 1180, 1159, 1147, 1112, 1060, 1022, 945, 910, 878, 840, 817, 777, 748, 721, 697, 671, 605, 581, 552, 530, 491, 477, 458. ¹H NMR (400 MHz, acetone- d_6) $\delta = 8.05$ (dq, J = 8.2, 0.9 Hz, 1H), 8.00–7.97 (m, 1H), 7.72 (d, J = 0.8 Hz, 1H), 7.58-7.54 (m, 2H), 7.48-7.44 (m, 1H), 7.29-7.23 (m, 2H), 3.77 (s, 3H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 190.13(C)$, 158.27(C), 143.77(C), 143.52(C), 140.20(C), 134.61(C), 133.34(CH), 132.96(CH), 131.85(CH),

128.76(CH), 127.36(CH), 126.10(CH), 123.94(CH), 112.35(CH), 93.12(C), 56.54(CH₃). LC/MS (retention time 4.56 min) m/z(ESI⁺) 395.00 (MH⁺, 100%), 416.90 (MNa⁺, 11.5%), 810.90 $(2MNa^{+}, 24.1\%)$. HRMS (ESI^{+}) : m/z calcd for $C_{16}H_{12}IO_{2}S^{+}$ [MH⁺]: 394.9597; found: 394.9601.

(2-Iodophenyl)(5-methoxy benzo[b]thiophen-2-yl)methanone 6e. According to general procedure B, scale: (2-iodophenyl)(5methoxybenzo[b]thiophen-2-yl)methanol 7e (0.311 g, 0.79 mmol) and MnO₂ (0.420 g, 4.83 mmol). The residue was purified by flash chromatography (0 to 20% of EtOAc in cyclohexane) to afford compound 6e as a yellow oil (0.256 g, 83%). IR: 3255, 3059, 2962, 2930, 2845, 2826, 2633, 1635, 1598, 1580, 1558, 1511, 1448, 1421, 1341, 1293, 1253, 1220, 1185, 1156, 1124, 1070, 1040, 1023, 943, 878, 854, 836, 809, 773, 745, 715, 681, 660, 636, 593, 555, 487. ¹H NMR (400 MHz, acetone- d_6) 8.04 (dd, J = 7.9, 1.2 Hz, 1H), 7.93 (d, J = 8.9Hz, 1H), 7.64-7.59 (m, 2H), 7.57 (dd, J = 7.6, 1.8 Hz, 1H), 7.50 (d, J = 2.4 Hz, 1H), 7.39-7.33 (m, 1H), 7.21 (dd, J = 8.9, 2.6)Hz, 1H), 3.85 (s, 3H). 13 C NMR (101 MHz, acetone- d_6) δ = 191.30(C), 159.06(C), 145.11(C), 144.02(C), 141.23(C), 140.59(CH), 136.63(C), 134.60(CH), 132.42(CH), 129.11(CH), 128.99(CH), 124.61(CH), 120.10(CH), 108.19(CH), 92.49(C), 55.84(CH₃). LC/MS (retention time 4.63 min) m/z (ESI⁺) 395.00 (MH⁺, 100%), 416.90 (MNa⁺, 16.1%), 810.90 (2MNa⁺, 20.8%). HRMS (ESI⁺): m/z calcd for $C_{16}H_{12}IO_2S^+$ [MH⁺]: 394.9597; found: 394.9594.

(2-Iodo-3-methoxyphenyl)(5-methoxy benzo[b]thiophen-2-yl) methanone 6f. According to general procedure B, scale: (2-iodo-3-methoxyphenyl) (5-methoxybenzo[b]thiophen-2-yl) methanol 7f (0.242 g, 0.57 mmol) and MnO₂ (0.299 g, 3.44 mmol). The residue was purified by flash chromatography (0 to 20% of EtOAc in cyclohexane) to afford compound 6f as a yellow solid (0.172 g, 71%), m.p. 129.1-130.6 °C. IR: 3076, 3059, 3008, 2959, 2926, 2839, 2826, 2350, 1632, 1600, 1560, 1515, 1449, 1418, 1341, 1307, 1262, 1223, 1192, 1179, 1160, 1056, 1023, 912, 876, 834, 807, 784, 763, 747, 715, 663, 613, 495. ¹H NMR (400 MHz, acetone- d_6) $\delta = 7.92$ (dt, J = 8.9, 0.6 Hz, 1H), 7.59 (d, J = 0.8 Hz, 1H), 7.55 (dd, J = 8.3, 7.5 Hz, 1H), 7.49 (d, J = 2.5 Hz, 1H), 7.22–7.16 (m, 2H), 7.08 (dd, J = 7.5, 1.3 Hz, 1H), 3.98 (s, 3H), 3.85 (s, 3H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 191.30(C)$, 159.31(C), 159.06(C), 147.34(C), 144.05(C), 141.25(C), 136.58(C), 134.36(CH), 130.74(CH), 124.62(CH), 120.88(CH), 119.99(CH), 112.94(CH), 108.18(CH), 84.72(C), 57.09(CH₃), 55.83(CH₃). LC/MS (retention time 4.54 min) m/z (ESI⁺) 425.00 (MH⁺, 100%), 446.80 (MNa⁺, 15.7%), 870.90 (2MNa⁺, 24.7%). HRMS (ESI⁺): m/z calcd for $C_{17}H_{14}$ - IO_3S^+ [MH⁺]: 424.9703; found: 424.9704.

(2-Iodo-4-methoxyphenyl)(5-methoxy benzo[b]thiophen-2-yl) methanone 6g. According to general procedure B, scale: according to general procedure 2, scale: (2-iodo-4methoxyphenyl)(5-methoxybenzo[b]thiophen-2-yl)methanol 7g (0.286 g, 0.62 mmol) and MnO_2 (0.360, 4.14 mmol). The residue was purified by flash chromatography (0 to 20% of EtOAc in cyclohexane) to afford compound 6g as a yellow oil (0.249 g, 95%). IR: 3074, 3002, 2959, 2935, 2834, 2777, 1710, 1638, 1586, 1556, 1510, 1485, 1451, 1437, 1421, 1386, 1342,

1296, 1284, 1217, 1180, 1157, 1121, 1070, 1019, 945, 868, 807, 764, 756, 715, 696, 676, 661, 621, 580, 572, 530, 486. ¹H NMR (400 MHz, acetone- d_6) $\delta = 7.92$ (dt, J = 8.9, 0.7 Hz, 1H), 7.66 (d, J = 1.0 Hz, 1H), 7.57 (d, J = 2.6 Hz, 1H), 7.54 (d, J = 8.6 Hz, 1H)1H), 7.51 (d, J = 2.6 Hz, 1H), 7.20 (dd, J = 8.9, 2.6 Hz, 1H), 7.15 (dd, J = 8.6, 2.4 Hz, 1H), 3.93 (s, 3H), 3.86 (s, 3H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 190.74(C)$, 162.16(C), 159.06(C), 144.67(C), 141.26(C), 136.99(C), 136.49(C), 134.15(CH), 130.82(CH), 126.23(CH), 124.59(CH), 119.87(CH), 114.45(CH), 108.17(CH), 93.66(C), 56.25(CH₃), 55.85(CH₃). LC/MS (retention time 4.70 min) m/z (ESI⁺) 425.00 (MH⁺, 100%), 447.00 (MNa⁺, 17.3%), 870.90 (2MNa⁺, 52.4%). HRMS (ESI⁺): m/z calcd for $C_{17}H_{14}IO_3S^+$ [MH⁺]: 424.9703; found: 424.9698.

(2-Iodo-5-methoxyphenyl)(5-methoxy benzo[b]thiophen-2-yl) methanone 6h. According to general procedure B, scale: according to general procedure 2, scale: (2-iodo-5-methoxyphenyl)(5methoxybenzo[b]thiophen-2-yl)methanol 7h (0.294 g, 0.69 mmol) and MnO₂ (0.367 g, 4.22 mmol). The residue was purified by flash chromatography (0 to 20% of EtOAc in cyclohexane) to afford compound 6h as a yellow oil (0.233 g, 80%). IR: 3065, 3002, 2392, 2934, 2832, 1710, 1644, 1602, 1586, 1582, 1509, 1451, 1422, 1401, 1390, 1342, 1318, 1295, 1265, 1231, 1213, 1178, 1155, 1106, 1070, 1044, 1023, 1008, 946, 916, 888, 800, 765, 714, 698, 680, 657, 607, 566, 560, 530, 490, 456. ¹H NMR (400 MHz, acetone- d_6) δ 7.93 (d, J = 8.9 Hz, 1H), 7.87 (d, J = 8.8 Hz, 1H), 7.67 (d, J = 1.0 Hz, 1H), 7.51 (d, I = 2.4 Hz, 1H), 7.21 (dd, I = 8.9, 2.4 Hz, 1H), 7.16 (d, I =3.1 Hz, 1H), 6.96 (dd, J = 8.8, 3.1 Hz, 1H), 3.88 (s, 3H), 3.86 (s, 3H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 190.97$ (C), 160.71(C), 159.08(C), 146.02(C), 143.89(C), 141.30(CH), 141.28(C), 136.65(C), 134.74(CH), 124.62(CH), 120.10(CH), 118.77(CH), 114.94(CH), 108.24(CH), 80.62(C), 56.12(CH₃), 55.85(CH₃). LC/MS (retention time 4.70 min) m/z (ESI⁺) 425.00 (MH⁺, 100%), 447.00 (MNa⁺, 18.1%), 870.90 (2MNa⁺, 33.5%). HRMS (ESI⁺): m/z calcd for C_{17} $H_{14}IO_3S^+$ [MH⁺]: 424.9703; found: 424.9699.

(5-((Tert-Butyldimethylsilyl)oxy)benzo[b]thiophen-2-yl)(2iodophenyl) methanone 6i. According to general procedure B, scale: (5-((tert-butyldimethylsilyl)oxy)benzo[b]thiophen-2-yl)(2iodophenyl)methanol 7i (0.420 g, 0.85 mmol) and MnO2 (0.443 g, 5.10 mmol). The residue was purified by flash chromatography (0 to 20% of EtOAc in cyclohexane) to afford compound 6i as a yellow oil (0.358 g, 85%). IR: 3059, 2954, 2928, 2885, 2856, 1712, 1648, 1599, 1583, 1549, 1510, 1471, 1462, 1437, 1390, 1361, 1324, 1288, 1256, 1222, 1158, 1126, 1108, 1069, 1040, 1016, 968, 939, 878, 868, 838, 813, 780, 741, 716, 704, 673, 642, 632, 616, 592, 552, 529, 487. ¹H NMR (400 MHz, acetone- d_6) δ = 8.04 (ddd, J = 7.9, 1.1, 0.5 Hz, 1H), 7.94 (dt, J = 8.8, 0.7 Hz, 1H), 7.63 (d, J = 0.9 Hz, 1H), 7.61 (dd, J = 0.9 Hz, 1H)7.2, 1.1 Hz, 1H), 7.58–7.54 (m, 1H), 7.51 (d, J = 2.4 Hz, 1H), 7.35 (ddd, J = 8.1, 7.3, 2.0 Hz, 1H), 7.18 (dd, J = 8.7, 2.4 Hz, 1H), 1.00 (s, 9H), 0.24 (s, 6H). ¹³C NMR (101 MHz, acetone d_6) $\delta = 191.35(C)$, 154.65(C), 145.11(C), 144.20(C), 141.45(C), 140.61(CH), 137.34(C), 134.56(CH), 132.44(CH), 129.12(CH), 129.00(CH), 124.75(CH), 123.87(CH), 116.47(CH), 92.46(C), 26.01(CH₃), 18.78(C), -4.36 (CH₃). LC/MS (retention time 6.14 min) m/z (ESI⁺) 495.10 (MH⁺, 100%), 517.10 (MNa⁺, 4.4%).

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HRMS (ESI⁺): m/z calcd for $C_{21}H_{24}IO_2SSi^+$ [MH⁺]: 495.0306; found: 495.0302.

(5-((Tert-Butyldimethylsilyl)oxy)benzo[b]thiophen-2-yl)(2-iodo-4-methoxyphenyl)methanone 6j. According to general procedure B, scale: (5-((tert-butyldimethylsilyl)oxy)benzo[b] thiophen-2-yl)(2-iodo-4-methoxyphenyl)methanol 7j (0.338 g, 0.64 mmol) and MnO2 (0.336 g, 3.86 mmol). The residue was purified by flash chromatography (0 to 20% of EtOAc in cyclohexane) to afford compound 6j as a yellow oil (0.225 g, 67%). IR: 3070, 3005, 2954, 2929, 2893, 2858, 1712, 1644, 1588, 1557, 1511, 1486, 1471, 1462, 1436, 1390, 1361, 1324, 1285, 1255, 1220, 1182, 1158, 1120, 1069, 1020, 968, 936, 880, 856, 838, 803, 780, 757, 740, 717, 696, 676, 625, 604, 590, 572, 529, 489. ¹H NMR (400 MHz, acetone- d_6) $\delta = 7.92$ (d, I = 9.5Hz, 1H), 7.66 (s, 1H), 7.57 (d, J = 2.4 Hz, 1H), 7.53 (d, J = 8.6Hz, 1H), 7.50 (d, J = 2.4 Hz, 1H), 7.15 (ddd, J = 8.6, 7.7, 2.5Hz, 2H), 3.92 (s, 3H), 1.01 (s, 9H), 0.25 (s, 6H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 190.73(C)$, 162.13(C), 154.58(C), 144.80(C), 141.43(C), 137.19(C), 136.91(C), 134.07(CH), 130.80(CH), 126.24(CH), 124.68(CH), 123.63(CH), 116.37(CH), 114.41(CH), 93.64(C), 56.23(CH), 26.02(CH₃), 18.78(C), -4.35 (CH₃). LC/MS (retention time 6.16 min) m/z (ESI⁺) 525.20 (MH⁺, 100%), 527.20 (MNa⁺, 1.9%). HRMS (ESI⁺): m/z calcd for $C_{22}H_{26}IO_3SSi^+$ [MH⁺]: 525.0411; found: 525.0413.

(5-((Tert-Butyldimethylsilyl)oxy)benzo[b]thiophen-2-yl)(2iodo-5-methoxyphenyl)methanone 6k. According to general procedure B, scale: according to general procedure 2, scale: (5-((tert-butyldimethylsilyl)oxy)benzo[b]thiophen-2-yl)(2-iodo-5-methoxyphenyl)methanol 7k (0.330 g, 0.63 mmol) and MnO₂ (0.326 g, 3.76 mmol). The residue was purified by flash chromatography (0 to 20% of EtOAc in cyclohexane) to afford compound 6k as a yellow oil (0.292 g, 89%). IR: 3059, 3002, 2954, 2929, 2885, 2856, 1711, 1651, 1599, 1564, 1549, 1510, 1461, 1437, 1402, 1390, 1361, 1324, 1287, 1257, 1232, 1213, 1182, 1155, 1106, 1069, 1046, 1009, 968, 939, 917, 883, 838, 802, 780, 741, 716, 679, 637, 617, 587, 490. ¹H NMR (400 MHz, acetone- d_6) δ = 7.93 (d, J = 8.8 Hz, 1H), 7.86 (d, J = 8.8 Hz, 1H), 7.67 (d, J = 0.9 Hz, 1H), 7.52 (d, J = 2.3 Hz, 1H), 7.20-7.12 (m, 2H), 6.96 (dd, J = 8.7, 3.0 Hz, 1H), 3.88 (s, 3H), 1.01 (s, 9H), 0.25 (s, 6H). ¹³C NMR (101 MHz, acetone- d_6) δ = 191.01(C), 160.73(C), 154.66(C), 146.02(C), 144.06(C), 141.50(C), 141.31(CH), 137.36(C), 134.70(CH), 124.75(CH), 123.87(CH), 118.77(CH), 116.51(CH), 114.95(CH), 80.60(C), 56.11(CH), 26.02(CH₃), 18.79(C), $-4.36(CH_3)$. (retention time 6.14 min) m/z (ESI⁺) 525.20 (MH⁺, 100%), 547.20 (MNa⁺, 3.5%). HRMS (ESI⁺): m/z calcd for $C_{22}H_{26}IO_3$ -SSi⁺ [MH⁺]: 525.0411; found: 525.0404.

(5-((Tert-Butyldimethylsilyl)oxy)benzo[b]thiophen-2-yl)(2-iodo-6-methoxyphenyl)methanone 6l. According to general procedure B, scale: (5-((tert-butyldimethylsilyl)oxy)benzo[b] thiophen-2-yl)(2-iodo-6-methoxyphenyl)methanol 7l (0.084 g, 0.16 mmol) and MnO_2 (0.165 g, 1.90 mmol). The residue was purified by flash chromatography (0 to 20% of EtOAc in cyclohexane) to afford compound 61 as a yellow solid (0.070 g, 83%), m.p. 124.8-125.5 °C. IR: 3535, 2953, 2928, 2856, 1660, 1585, 1566, 1513, 1456, 1428, 1325, 1288, 1257, 1221,

1159, 1114, 1064, 1025, 966, 938, 870, 838, 822, 776, 752, 742, 717, 674, 640, 613, 588, 562, 500, 465. ¹H NMR (400 MHz, acetone- d_6) $\delta = 7.92$ (dt, J = 8.8, 0.7 Hz, 1H), 7.62 (d, J = 0.7Hz, 1H), 7.55 (dd, J = 7.5, 1.3 Hz, 1H), 7.48 (d, J = 2.4 Hz, 1H), 7.31-7.23 (m, 2H), 7.19-7.14 (m, 1H), 3.77 (s, 3H), 1.01 (s, 9H), 0.24 (s, 6H). ¹³C NMR (101 MHz, acetone- d_6) δ = 158.28(C), 154.61(C), 144.57(C), 141.55(C), 137.16(C), 134.71(C), 132.94(CH), 132.92(CH), 131.85(CH), 124.77(CH), 123.61(CH), 116.36(CH), 112.34(CH), 93.13(C), 56.54(CH), 26.03(CH₃), 18.79(C), -4.35 (CH₃). LC/MS (retention time 5.99 min) m/z (ESI⁺) 525.10 (MH⁺, 100%), 547.00 (MNa⁺, 11.3%). HRMS (ESI⁺): m/z calcd for $C_{22}H_{26}IO_3$ -SSi⁺ [MH⁺]: 525.0411; found: 525.0406.

(5-Fluorobenzo[b]thiophen-2-yl)(2-iodo-5-methoxyphenyl) methanone 6m. According to general procedure B, scale: (5-fluoro benzo[b]thiophen-2-yl)(2-iodo-5-methoxyphenyl) methanol 7m (0.206 g, 0.50 mmol) and MnO₂ (0.259 g, 2.97 mmol). The residue was purified by flash chromatography (0 to 20% of EtOAc in cyclohexane) to afford compound 6m as a yellow oil (0.180 g, 88%). IR: 3089, 3073, 3000, 2935, 2845, 1647, 1585, 1570, 1515, 1461, 1437, 1437, 1389, 1330, 1319, 1289, 1268, 1234, 1204, 1186, 1149, 1138, 1105, 1069, 1036, 1008, 956, 881, 805, 769, 754, 724, 713, 673, 653, 600, 584, 488, 463. ¹H NMR (400 MHz, acetone- d_6) $\delta = 8.16-8.08$ (m, 1H), 7.90-7.84 (m, 1H), 7.81-7.71 (m, 2H), 7.47-7.39 (m, 1H), 7.21–7.16 (m, 1H), 7.00–6.95 (m, 1H), 3.89–3.87 (m, 3H). ¹³C NMR (101 MHz, acetone- d_6) $\delta = 190.99(C)$, 161.86(C, d, J =240.4 Hz), 160.76(C), 145.67(C), 145.36 (C), 141.39(CH), 141.19(C, d, J = 9.1 Hz), 139.66(C), 134.47(CH, d, J = 5.1 Hz), 125.79(CH, J = 9.1 Hz), 118.95(CH), 117.89(CH, d, J = 26.3)Hz), 115.04(CH), 112.28(CH, d, J = 23.2 Hz), 80.54(C), 56.13(CH₃). ¹⁹F NMR (376 MHz, acetone- d_6) $\delta = -118.54$. LC/ MS (retention time 4.78 min) m/z (ESI⁺) 412.90 (MH⁺, 100%), 434.90 (MNa⁺, 30.0%), 844.00 (2MNa⁺, 26.5%). HRMS (ESI⁺): m/z calcd for $C_{16}H_{11}FIO_2S^+$ [MH⁺]: 412.9503; found: 412.9494.

General procedure C for the palladium-catalysed cyclisation of iodoketone 6 into tetracyclic derivative 4. In a sealable tube was added iodoketone 6 (0.30 mmol) in DMF (4 mL) under an argon atmosphere. Then Pd(OAc)2 (0.004 g, 0.018 mmol), Cy₃P·HBF₄ (0.012 g, 0.03 mmol) and K₂CO₃ (0.084 g, 0.61 mmol) were added successively. After stirring for 15 min at room temperature, the tube was sealed and heated during 16 h at 130 °C. After cooling, the reaction mixture was filtered through a sintered-glass funnel. Water (10 mL) and DCM (10 mL) were added, the aqueous layer was separated and extracted with ethyl acetate (2 × 10 mL). The combined organic phases were washed with brine (10 mL), dried over Na2SO4, filtered and concentrated under reduced pressure. The crude was purified by flash chromatography (DCM or MeOH/DCM) to afford the desired product.

10-Methoxy-6H-benzo[b]indeno[1,2-d]thiophen-6-one According to general procedure C, scale: benzo[b]thiophen-2yl(2-iodo-3-methoxyphenyl)methanone 6a (0.124 g, 0.31 mmol), Pd(OAc)₂ (0.004 g, 0.018 mmol), Cy₃P·HBF₄ (0.012 g, 0.03 mmol), K_2CO_3 (0.087 g, 0.63 mmol). The residue was purified by flash chromatography (DCM) to afford compound

4a as a red solid (0.068 g, 82%), m.p. 187.0-189.4 °C. IR: 3100, 3000, 2954, 2922, 2845, 1929, 1697, 1600, 1487, 1467, 1435, 1411, 1388, 1328, 1260, 1201, 1182, 1163, 1087, 1052, 985, 838, 828, 857, 801, 770, 762, 750, 731, 682, 628, 599, 551, 520, 498, 463. ¹H NMR (500 MHz, DMSO- d_6) δ = 8.60–8.52 (m, 1H), 8.09-8.02 (m, 1H), 7.54-7.48 (m, 2H), 7.27 (dt, J = 5.1, 2.6 Hz, 2H), 7.09 (td, J = 4.6, 2.5 Hz, 1H), 4.02 (s, 3H). ¹³C NMR (126 MHz, DMSO- d_6) $\delta = 186.14(C)$, 152.54(C), 151.44(C), 147.18(C), 137.44(C), 134.10(C), 131.65(C), 130.51(CH), 127.62(CH), 126.51(CH), 125.69(CH), 125.62(C), 124.32(CH), 120.00(CH), 116.57(CH), 55.81(CH₃). LC/MS (retention time 4.72 min) m/z (ESI⁺) 267.10 (MH⁺, 100%), 289.10 (MNa⁺, 7.7%). HRMS (ESI⁺): m/z calcd for $C_{16}H_{11}O_2S^+$ [MH⁺]: 267.0474; found: 267.0465.

9-Methoxy-6H-benzo[b]indeno[1,2-d]thiophen-6-one According to general procedure C, scale: benzo[b]thiophen-2yl(2-iodo-4-methoxyphenyl)methanone **6b** (0.165 g, mmol), Pd(OAc)₂ (0.005 g, 0.02 mmol), Cy₃P·HBF₄ (0.016 g, 0.04 mmol), K₂CO₃ (0.116 g, 0.84 mmol). The residue was purified by flash chromatography (DCM) to afford compound **4b** as an orange solid (0.098 g, 88%), m.p. 201.8-203.3 °C. IR: 3054, 998, 2352, 1890, 1719, 1691, 1599, 1499, 1467, 1428, 1413, 1383, 1293, 1270, 1241, 1222, 1165, 1147, 1072, 1019, 965, 942, 865, 856, 828, 770, 761, 730, 706, 691, 648, 667, 621, 509, 491, 482. ¹H NMR (500 MHz, DMSO- d_6) $\delta = 8.38-8.36$ (m, 1H), 8.14-8.05 (m, 1H), 7.58-7.53 (m, 2H), 7.42 (d, J = 8.1 Hz, 1H), 7.33 (d, J = 2.2 Hz, 1H), 6.73 (dd, J = 8.1, 2.2 Hz, 1H), 3.92 (s, 3H). 13C NMR (126 MHz, DMSO- d_6) $\delta = 186.97$ (C), 150.28(C), 146.75(C), 141.56(C), 137.55(C), 131.13(C), 128.35(C), 127.47(CH), 125.99(CH), 125.32(CH), 124.55(CH), 124.11(CH), 110.26(CH), 109.00(CH), 55.75(CH₃). LC/MS (retention time 4.61 min) m/z (ESI⁺) 267.10 (MH⁺, 100%), 289.10 (MNa⁺, 4.2%), 555.10 (2MNa⁺, 3.5%). HRMS (ESI⁺): m/z calcd for $C_{16}H_{10}O_2S^+$ [MH⁺]: 267.0474; found: 267.0475.

8-Methoxy-6H-benzo[b]indeno[1,2-d]thiophen-6-one According to general procedure C, scale: benzo[b]thiophen-2yl(2-iodo-5-methoxyphenyl)methanone 6c (0.197 g, 0.50 mmol), Pd(OAc)₂ (0.006 g, 0.03 mmol), Cy₃P·HBF₄ (0.018 g, 0.05 mmol), K₂CO₃ (0.140 g, 1.01 mmol). The residue was purified by flash chromatography (DCM) to afford compound 4c as a red solid (0.117 g, 88%), m.p. 159.4-161.0 °C. IR: 3092, 3059, 3013, 2951, 2842, 2328, 1696, 1618, 1593, 1494, 1468, 1435, 1387, 1330, 1288, 1261, 1221, 1191, 1157, 1139, 1086, 1057, 1019, 944, 909, 892, 832, 817, 770, 742, 726, 710, 681, 631, 573, 542, 500. ¹H NMR (500 MHz, DMSO- d_6) δ = 8.32-8.25 (m, 1H), 8.09 (ddd, J = 7.1, 3.9, 3.0 Hz, 1H), 7.65 (d, $J = 8.0 \text{ Hz}, 1\text{H}, 7.55 \text{ (qt, } J = 9.4, 5.5, 4.7 \text{ Hz}, 2\text{H}), 7.02 \text{ (d, } J = 9.4, 5.5, 4.7 \text{ Hz}, 2\text{Hz}, 2\text{H$ 2.4 Hz, 1H), 6.92 (dd, J = 8.0, 2.5 Hz, 1H), 3.81 (s, 3H). ¹³C NMR (126 MHz, DMSO- d_6) $\delta = 186.10(C)$, 160.06(C), 147.62(C), 138.48(C), 134.27(C), 131.29(C), 131.15(C), 128.28(CH), 126.29(CH), 124.97(CH), 124.69(CH), 121.48(CH), 116.39(CH), 112.01(CH), 55.72(CH₃). LC/MS (retention time 4.68 min) m/z (ESI⁺) 267.10 (MH⁺, 100.0%), 289.0 (MNa⁺, 8.7%), 555.20 (2MNa⁺, 3.6%). HRMS (ESI⁺): m/z calcd for $C_{16}H_{10}O_2S^+$ [MH⁺]: 267.0474; found: 267.0465.

7-Methoxy-6H-benzo[b]indeno[1,2-d]thiophen-6-one According to general procedure C, scale: benzo[b]thiophen-2yl(2-iodo-6-methoxyphenyl)methanone 6d (0.056 g, 0.14 mmol), Pd(OAc)₂ (0.002 g, 0.01 mmol), Cy₃P·HBF₄ (0.005 g, 0.02 mmol), K₂CO₃ (0.040 g, 0.28 mmol). The residue was purified by flash chromatography (DCM) to afford compound 4d as an orange solid (0.025 g, 67%), m.p. 178.6-183.7 °C. IR: 3372, 3263, 3067, 3002, 2978, 2923, 2847, 2839, 1662, 1690, 1597, 1501, 1478, 1460, 1435, 1415, 1386, 1279, 1246, 1200, 1165, 1138, 1069, 1049, 975, 881, 851, 825, 794, 783, 774, 758, 732, 702, 681, 647, 580, 503. ¹H NMR (500 MHz, DMSO- d_6) δ = 8.32-8.28 (m, 1H), 8.15-8.10 (m, 1H), 7.58-7.51 (m, 2H), 7.49 (dd, J = 8.7, 7.1 Hz, 1H), 7.43–7.35 (m, 1H), 7.02 (d, J =8.6 Hz, 1H), 3.88 (s, 3H). 13 C NMR (126 MHz, DMSO- d_6) δ = 184.56(C), 157.22(C), 150.16(C), 146.80(C), 141.14(C), 137.09(CH), 136.81(C), 131.53(C), 127.69(CH), 126.37(CH), 125.02(CH), 124.20(CH), 120.00(C), 114.88(CH), 113.76(CH), 55.75(CH₃). LC/MS (retention time 4.20 min) m/z (ESI⁺) 267.10 (MH⁺, 100%), 289.00 (MNa⁺, 13.0%), 555.10 (2MNa⁺, 51.1%). HRMS (ESI⁺): m/z calcd for $C_{16}H_{11}O_2S^+$ [MH⁺]: 267.0474; found: 267.0474.

2-Methoxy-6H-benzo[b]indeno[1,2-d]thiophen-6-one According to general procedure C, scale: (2-iodophenyl)(5methoxybenzo[b]thiophen-2-yl)methanone 6e (0.213 g, 0.54 mmol), Pd(OAc)₂ (0.006 g, 0.03 mmol), Cy₃P·HBF₄ (0.020 g, 0.05 mmol), K_2CO_3 (0.151 g, 1.09 mmol). The residue was purified by flash chromatography (DCM) to afford compound **4e** as an orange solid (0.119 g, 83%), m.p. 168.7–170.7 °C. IR: 3062, 3049, 3000, 2956, 2931, 2826, 1719, 1688, 1606, 1502, 1455, 1435, 1419, 1378, 1331, 1310, 1287, 1272, 1232, 1204, 1188, 1130, 1074, 1058, 1023, 973, 936, 877, 857, 824, 810, 766, 758, 721, 696, 653, 615, 566, 540, 482. ¹H NMR (500 MHz, DMSO- d_6) δ 7.97 (d, J = 9.0 Hz, 1H), 7.80 (dt, J = 7.3, 0.8 Hz, 1H), 7.62 (d, J = 2.5 Hz, 1H), 7.47 (td, J = 7.5, 1.1 Hz, 1H), 7.42 (dt, J = 7.2, 0.9 Hz, 1H), 7.25 (ddd, J = 8.0, 7.2, 0.9 Hz, 1H), 7.17 (dd, J = 9.0, 2.5 Hz, 1H), 3.92 (s, 3H). 13C NMR (126 MHz, DMSO-d₆) δ = 186.49(C), 158.45(C), 152.05(C), 140.11(C), 139.36(C), 136.92(C), 136.23(C), 134.37(CH), 132.44(C), 128.43(CH), 125.65(CH), 123.55(CH), 120.66(CH), 118.89(CH), 105.55(CH), 55.76(CH₃). LC/MS (retention time 4.63 min) m/z (ESI⁺) 267.10 (MH⁺, 100%), 289.20 (MNa⁺, 5.2%), 555.20 (2MNa⁺, 1.9%). HRMS (ESI⁺): m/z calcd for C₁₆- $H_{10}NaO_2S^+$ [MNa⁺]: 289.0294; found: 289.0299.

2,10-Dimethoxy-6*H*-benzo[*b*]indeno[1,2-*d*]thiophen-6-one 4f. According to general procedure C, scale: (2-iodo-3methoxyphenyl)(5-methoxybenzo[b]thiophen-2-yl)methanone 6f (0.116 g, 0.27 mmol), Pd(OAc)₂ (0.003 g, 0.02 mmol), Cy₃-P·HBF₄ (0.010 g, 0.03 mmol), K₂CO₃ (0.076 g, 0.55 mmol). The residue was purified by flash chromatography (DCM) to afford compound 8 cycle as a red solid (0.070 g, 86%), m.p. 198.0-205.8 °C. IR: 3122, 2981, 2943, 2918, 2899, 2838, 1728, 1690, 1599, 1491, 1444, 1414, 1376, 1337, 1307, 1266, 1224, 1199, 1180, 1160, 1123, 1064, 1027, 973, 927, 851, 815, 799, 742, 679, 640, 569, 550, 485. ¹H NMR (500 MHz, DMSO- d_6) δ = 8.07 (d, J = 2.6 Hz, 1H), 7.90 (d, J = 8.9 Hz, 1H), 7.31-7.23(m, 2H), 7.14 (dd, J = 8.9, 2.6 Hz, 1H), 7.09 (q, J = 4.6, 4.0 Hz,

1H), 4.03 (s, 3H), 3.89 (s, 3H). 13 C NMR (126 MHz, DMSO- d_6) $\delta = 186.04(C), 157.65(C), 151.93(C), 151.21(C), 139.85(C),$ 137.40(C), 135.15(C), 132.76(C), 130.30(CH), 125.68(C), 124.88(CH), 119.86(CH), 118.26(CH), 116.56(CH), 107.63(CH), 55.91(CH₃), 54.94(CH₃). LC/MS (retention time 4.76 min) m/z(ESI⁺) 297.10 (MH⁺, 100%), 319.00 (MNa⁺, 9.6%), 615.20 $(2MNa^{+}, 15.5\%)$. HRMS (ESI^{+}) : m/z calcd for $C_{17}H_{13}O_{3}S^{+}$ [MH⁺]: 297.0580; found: 297.0578.

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2,9-Dimethoxy-6*H*-benzo[*b*]indeno[1,2-*d*]thiophen-6-one 4g. According to general procedure C, scale: (2-iodo-4methoxyphenyl)(5-methoxybenzo[b]thiophen-2-yl)methanone 6g (0.169 g, 0.40 mmol), Pd(OAc)₂ (0.005 g, 0.02 mmol), Cy₃-P·HBF₄ (0.015 g, 0.04 mmol), K₂CO₃ (0.114 g, 0.82 mmol). The residue was purified by flash chromatography (DCM) to afford compound 4g as an orange solid (0.100 g, 84%), m.p. 194.2-196.0 °C. IR: 3106, 3070, 3019, 2983, 2926, 2902, 2861, 2826, 2358, 2326, 1694, 1595, 1500, 1452, 1439, 1409, 1369, 1341, 1312, 1282, 1237, 1204, 1169, 1147, 1122, 1084, 1061, 1018, 976, 913, 851, 822, 813, 807, 793, 760, 737, 700, 691, 664, 655, 632, 619, 565, 509, 484. ¹H NMR (500 MHz, DMSO d_6) $\delta = 7.93$ (d, J = 9.0 Hz, 1H), 7.58 (d, J = 2.5 Hz, 1H), 7.35 (d, J = 8.1 Hz, 1H), 7.30 (d, J = 2.2 Hz, 1H), 7.13 (dd, J = 9.0)2.5 Hz, 1H), 6.66 (dd, J = 8.1, 2.2 Hz, 1H), 3.90 (s, 3H), 3.87 (s, 3H). ¹³C NMR (126 MHz, DMSO- d_6) $\delta = 184.70$ (C), 164.42(C), 158.23(C), 149.42(C), 141.39(C), 139.27(C), 138.62(C), 132.16(C), 128.34(C), 125.01(CH), 124.97(CH), 117.75(CH), 109.61(CH), 109.17(CH), 105.81(CH), 55.51(2 × CH₃). LC/MS (retention time 4.66 min) m/z (ESI⁺) 297.10 (MH⁺, 100%), 319.00 (MNa⁺, 4.9%), 615.10 (2MNa⁺, 11.9%). HRMS (ESI⁺): m/z calcd for $C_{17}H_{13}O_3S^+$ [MH⁺]: 297.0580; found: 297.0580.

2,8-Dimethoxy-6*H*-benzo[*b*]indeno[1,2-*d*]thiophen-6-one 4h. According to general procedure C, scale: (2-iodo-5methoxyphenyl)(5-methoxybenzo[b]thiophen-2-yl)methanone 6h (0.164 g, 0.39 mmol), Pd(OAc)₂ (0.004 g, 0.02 mmol), Cy₃-P·HBF₄ (0.014 g, 0.04 mmol), K₂CO₃ (0.108 g, 0.78 mmol). The residue was purified by flash chromatography (DCM) to afford compound 4h as a brown solid (0.080 g, 70%), m.p. 192.4-193.9 °C. IR: 3383, 2975, 3956, 2935, 2877, 2850, 2826, 1885, 1720, 1700, 1606, 1502, 1487, 1469, 1458, 1445, 1432, 1416, 1375, 1328, 1310, 1278, 1269, 1234, 1200, 1132, 1073, 1057, 1020, 971, 884, 833, 822, 809, 787, 768, 761, 738, 657, 645, 583, 580, 541, 474. ¹H NMR (500 MHz, DMSO- d_6) $\delta =$ 7.94 (d, J = 9.0 Hz, 1H), 7.66 (d, J = 8.0 Hz, 1H), 7.55 (d, J =2.5 Hz, 1H), 7.15 (dd, J = 9.0, 2.5 Hz, 1H), 6.97 (d, J = 2.5 Hz, 1H), 6.88 (dd, J = 8.0, 2.5 Hz, 1H), 3.90 (s, 3H), 3.80 (s, 3H). ¹³C NMR (126 MHz, DMSO- d_6) $\delta = 185.47$ (C), 159.73(C), 152.54(C), 139.96(C), 138.18(C), 135.18(C), 131.96(C), 131.23(C), 125.04(CH), 120.91(CH), 118.25(CH), 116.37(CH), 111.40(CH), 105.90(CH), 55.47(CH₃), 55.38(CH₃). LC/MS (retention time 4.73 min) m/z (ESI⁺) 297.10 (MH⁺, 100%), 319.00 (MNa⁺, 9.1%), 616.10 (2MNa⁺, 13.7%). HRMS (ESI⁺): m/z calcd for $C_{17}H_{13}O_3S^+$ [MH⁺]: 297.0580; found: 297.0574.

2-Hydroxy-6H-benzo[b]indeno[1,2-d]thiophen-6-one 4i. According to general procedure C, scale: (5-((tert-butyldimethylsilyl)oxy)

benzo[b]thiophen-2-yl)(2-iodophenyl)methanone 6i (0.235 g, 0.48 mmol), Pd(OAc)₂ (0.005 g, 0.02 mmol), Cy₃P·HBF₄ (0.018 g, 0.05 mmol), K₂CO₃ (0.132 g, 0.96 mmol). The residue was purified by flash chromatography (DCM/MeOH: 99/1) to afford compound 4i as a red solid (0.088 g, 74%), m.p. 265.4-270.8 °C. IR: 3372, 3321, 3054, 2921, 2847, 2328, 1720, 1680, 1607, 1504, 1455, 1424, 1402, 1364, 1328, 1279, 1237, 1201, 1141, 1130, 1075, 1056, 980, 883, 859, 848, 818, 802, 788, 759, 724, 694, 654, 614, 563, 543, 512. ¹H NMR (500 MHz, DMSO- d_6) $\delta = 9.95$ (s, 1H), 7.90 (d, J = 8.9 Hz, 1H), 7.57 (dt, J = 7.3, 0.8 Hz, 1H), 7.53 (d, J = 2.4 Hz, 1H), 7.48 (td, J = 7.5, 1.1 Hz, 1H), 7.43 (dt, J = 7.2, 0.9 Hz, 1H), 7.28–7.23 (m, 1H), 7.09 (dd, J = 8.9, 2.4 Hz, 1H). ¹³C NMR (126 MHz, DMSO- d_6) $\delta = 186.55(C), 156.48(C), 151.75(C), 139.55(C), 138.64(C),$ 136.74(C), 136.34(C), 134.50(CH), 132.72(C), 128.37(CH), 125.66(CH), 123.61(CH), 120.03(CH), 119.02(CH), 108.27(CH). LC/ MS (retention time 3.71 min) m/z (ESI⁺) 253.00 (MH⁺, 100%), 275.00 (MNa⁺, 14.2%), 527.00 (2MNa⁺, 5.0%). HRMS (ESI⁺): m/z calcd for C₁₅H₉O₂S⁺ [MH⁺]: 253.0318; found: 253.0325.

2-Hydroxy-9-methoxy-6H-benzo[b]indeno[1,2-d]thiophen-6-one According to general procedure C, scale: (5-((tert-butyldimethylsilyl) oxy)benzo[b]thiophen-2-yl)(2-iodo-4-methoxyphenyl)methanone 6j (0.141 g, 0.27 mmol), Pd(OAc)₂ (0.003 g, 0.02 mmol), Cy₃P·HBF₄ (0.010 g, 0.03 mmol), K₂CO₃ (0.074 g, 0.54 mmol). The residue was purified by flash chromatography (DCM/MeOH: 99/1) to afford compound 4j as a brown solid (0.060 g, 79%), m.p. 288.8-292.4 °C. IR: 3345, 3226, 3008, 2925, 2850, 2828, 1673, 1601, 1504, 1460, 1417, 1363, 1343, 1298, 1242, 1198, 1181, 1156, 1143, 1131, 1074, 1056, 1024, 982, 926, 846, 802, 765, 739, 699, 662, 624, 603, 567, 506, 487. ¹H NMR (500 MHz, DMSO- d_6) δ = 9.89 (s, 1H), 7.88 (d, J = 8.9 Hz, 1H), 7.55 (d, J = 2.3 Hz, 1H), 7.37 (d, J = 8.1 Hz, 1H), 7.10 (d, J = 2.2 Hz, 1H), 7.07 (dd, J = 8.9, 2.4 Hz, 1H), 6.68 (dd, J = 8.1, 1)2.2 Hz, 1H), 3.89 (s, 3H). 13 C NMR (126 MHz, DMSO-d₆) δ = 185.43(C), 164.59(C), 156.42(C), 149.58(C), 141.96(C), 138.55(C), 128.53(C), 125.62(CH), 125.54(CH), 132.70(C), 118.57(CH), 110.15(CH), 108.68(CH), 108.23(CH), 55.96(CH₃). LC/ MS (retention time 3.77 min) m/z (ESI⁺) 283.00 (MH⁺, 100%), 305.10 (MNa⁺, 7.1%), 587.10 (2MNa⁺, 17.2%). HRMS (ESI⁺): m/z calcd for $C_{16}H_{11}O_3S^+$ [MH⁺]: 283.0423; found: 283.0421.

2-Hydroxy-8-methoxy-6H-benzo[b]indeno[1,2-d]thiophen-6-one 4k. According to general procedure C, scale: (5-((tert-butyldimethylsilyl) oxy)benzo[b]thiophen-2-yl)(2-iodo-5-methoxyphenyl)methanone 6k (0.195 g, 0.37 mmol), Pd(OAc)₂ (0.004 g, 0.02 mmol), Cy₃P·HBF₄ $(0.014 \text{ g}, 0.04 \text{ mmol}), \text{ K}_2\text{CO}_3 (0.103 \text{ g}, 0.74 \text{ mmol}).$ The residue was purified by flash chromatography (DCM/MeOH: 99/1) to afford compound 4k as a dark brown solid (0.060 g, 57%), m.p. 224-229.7 °C. IR: 3319, 3002, 2962, 2397, 2921, 2853, 2834, 2350, 1906, 1700, 1674, 1621, 1600, 1498, 1471, 1462, 1421, 1363, 1338, 1260, 1242, 1222, 1198, 1189, 1140, 1056, 1029, 979, 926, 917, 880, 848, 823, 808, 796, 770, 741, 693, 657, 647, 625, 576, 512. ¹H NMR (500 MHz, DMSO- d_6) δ 9.92 (s, 1H), 7.87 (d, J = 8.9 Hz, 1H), 7.48 (d, J = 2.3 Hz, 1H), 7.45 (d, J = 8.0 Hz, 1H), 7.08 (dd, J = 8.9, 2.4 Hz, 1H), 7.00 (d, J = 2.5 Hz, 1H), 6.92 (dd, J = 8.1, 2.5 Hz, 1H), 3.80 (s, 3H). ¹³C NMR (126 MHz, DMSO- d_6) $\delta = 186.12$ (C), 159.86(C), 156.35(C), 152.78(C), 138.77(C), 138.52(C), 135.12(C), 132.49(C), 131.51(C), 125.59(CH), 120.87(CH), 119.06(CH), 116.35(CH), 112.01(CH), 108.35(CH), 55.69(CH₃). LC/MS (retention time 3.86 min) m/z (ESI⁺) **RSC Medicinal Chemistry**

283.00 (MH⁺, 100%), 305.00 (MNa⁺, 10.3%). HRMS (ESI⁺): m/z calcd for $C_{16}H_{11}O_3S^+$ [MH⁺]: 283.0423; found: 283.0429.

2-Hydroxy-7-methoxy-6H-benzo[b]indeno[1,2-d]thiophen-6-one According to general procedure C, scale: (5-((tert-butyldimethylsilyl) oxy)benzo[b]thiophen-2-yl)(2-iodo-6-methoxyphenyl)methanone 6l (0.050 g, 0.10 mmol), Pd(OAc)₂ (0.001 g, 0.01 mmol), Cv₃P·HBF₄ (0.004 g, 0.01 mmol), K₂CO₃ (0.026 g, 0.19 mmol). The residue was purified by flash chromatography (DCM/MeOH: 99/1) to afford compound 41 as a brown solid (0.014 g, 51%), m.p. 264.7-269.9 °C. IR: 3369, 3324, 3097, 3065, 2924, 2853, 1739, 1683, 1600, 1508, 1468, 1424, 1361, 1341, 1288, 1254, 1231, 1177, 1160, 1135, 1077, 1053, 994, 930, 867, 855, 790, 782, 733, 692, 676, 652, 583, 528, 511. ¹H NMR (500 MHz, DMSO- d_6) δ = 9.91 (s, 1H), 7.90 (dd, J = 8.9, 3.5 Hz, 1H), 7.51 (d, J = 2.2 Hz, 1H), 7.51–7.48 (m, 1H), 7.21 (d, J = 7.0 Hz, 1H), 7.08–7.05 (m, 1H), 7.03 (d, J = 8.7 Hz, 1H), 3.89 (s, 3H). ¹³C NMR (126 MHz, DMSO- d_6) $\delta = 184.77$ (C), 157.38(C), 156.60(C), 149.37(C), 141.53(C), 138.01(C), 137.80(C), 137.27(CH), 133.03(C), 125.82(CH), 120.20(C), 118.54(CH), 114.82(CH), 113.37(CH), 108.17(CH), 55.90(CH₃). LC/MS (retention time 3.33 min) m/z (ESI⁺) 283.10 (MH⁺, 100%), 305.10 (MNa⁺, 10.4%), 587.20 $(2MNa^{+}, 47.4\%)$. HRMS (ESI^{+}) : m/z calcd for $C_{16}H_{11}O_{3}S^{+}$ $[MH^{+}]$: 283.0423; found: 283.0425.

2-Fluoro-8-methoxy-6H-benzo[b]indeno[1,2-d]thiophen-6-one 4m. Following general procedure C, scale: (5-fluorobenzo[b] thiophen-2-yl)(2-iodo-5-methoxyphenyl)methanone 6m (0.139 g, 0.34 mmol), Pd(OAc)₂ (0.004 g, 0.02 mmol), Cy₃P·HBF₄ (0.013 g, 0.04 mmol), K₂CO₃ (0.097 g, 0.70 mmol). The residue was purified by flash chromatography (DCM) to afford compound 4m as a purple solid (0.083 g, 87%), m.p. 196.6-198.7 °C. IR: 3092, 3032, 2994, 2956, 1703, 1618, 1599, 1499, 1468, 1438, 1418, 1371, 1333, 1288, 1260, 1225, 1181, 1143, 1120, 1056, 1016, 976, 922, 876, 854, 820, 797, 768, 740, 653, 640, 573, 504. ¹H NMR (500 MHz, DMSO-*d*₆) δ 8.16–8.07 (m, 2H), 7.74-7.67 (m, 1H), 7.42 (tdt, J = 9.1, 2.2, 1.0 Hz, 1H),7.04 (dt, J = 2.9, 1.5 Hz, 1H), 6.94 (ddt, J = 8.0, 2.5, 1.2 Hz, 1H), 3.83 (s, 3H). ¹³C NMR (126 MHz, DMSO- d_6) δ = 185.58(C), 160.83(C, J = 243.2 Hz), 159.93(C), 152.70(C, J = 5.0Hz), 143.03(C), 137.89(C), 136.56(C), 131.78(C, J = 10.1 Hz), 130.88(C), 126.38(CH, J = 8.8 Hz), 121.32(CH), 116.55(CH, J = 8.8 Hz)26.5 Hz), 116.54(CH), 111.78(CH), 109.52(CH, J = 22.7 Hz), 55.52(CH₃), ¹⁹F NMR (471 MHz, DMSO- d_6) $\delta = -115.51$ (td, J =9.0, 4.7 Hz). LC/MS (retention time 4.77 min) m/z (ESI⁺) 285.10 (MH⁺, 100%), 307.10 (MNa⁺, 24.3%), 591.10 (2MNa⁺, 6.0%). HRMS (ESI⁺): m/z calcd for $C_{16}H_9FO_2S^+$ [MH⁺]: 285.0386; found: 285.0387.

Biological evaluations

DYRK1A/DYRK1B kinases inhibition assays. Human Dyrk1A was expressed and purified as described earlier. 48 Dyrk1B were purchased from Life Technologies.⁵⁰ Woodtide substrate peptide for Dyrk1A and Dyrk1B (KKISGRLSPIMTEQ) were custom synthesized at the Department of Medical Biochemistry and Molecular Biology, Saarland University, Homburg, Germany. Kinase inhibition assays for Dyrk1A and Dyrk1B were performed as described previously, in the presence of 15 mM ATP. 48 The calculated IC50 values are representative of at least two independent determinations and 3,3'-(2,4-thienediyl)dipyridine was used as the positive control.

The larger panel of kinases shown in Table 2 was screened by the SelectScreen Kinase Profiling Service, Thermo Fisher Scientific, Madison, USA and the Kinase Profiler service, Eurofins/CEREP Celle L'Evescault, France. For each kinase, ATP concentrations were set at ATP Km.

Cell viability of compounds - MTT protocol. Cell viability is evaluated through the MTT colorimetric assay. The MTT assay is based on protocol described by Mosmann. 92 The assay was optimized for cell line used in the experiment. U-87MG cells or U373MG cells (human malignant gliomas, respectively HTB14 and HTB17 ATCC) are plated at a density of 10 000 cells per well into 96 well culture plates. Cells are incubated overnight at 37 °C in 5% CO2 in MEM (modified Eagle's medium) media supplemented with 10% FBS (fetal bovine serum). The following day, cells are treated in triplicated with the compounds (1-200 µM) in 1% DMSO or with vehicle control (1% DMSO). After 72 h, the cells are incubated with 20 µL of MTT at 5 mg mL-1 (Sigma Aldrich M2128) for 3 h at 37 °C. The medium is the removed and 100 µl of 0.1 N HCl in isopropanol is added in each well for 15 min. Absorbance is measured by a plate reader at 570 nm and the value measured at 690 nm was subtracted. Data are the mean \pm SD of at least three independent experiments.

Microsomal stability assays. Protocol for metabolic stability was adapted from different published procedures. 93-95

Compounds (10 µM) were preincubated with phosphate buffer (pH 7.4, 0.1 M) and rat liver microsomes (0.15 mg) for 10 min at 37 °C then NADPH (1 mM) was added to start the reaction. Final concentration of DMSO was 0.5% and total reaction volume was 500 μL. Aliquots (50 μL) were taken at desired timepoints (0, 5, 15, 30, 45, 60 min) and diluted with a solution of cold acetonitrile to stop the reaction (100 µL, containing 0.5 mg mL⁻¹ BHT as internal standard). After centrifugation, supernatants were analyzed by gradient UHPLC-MS method using Agilent 1290 series (Agilent POROSHELL 120 SB-C18 column, 2.7 µm, 2.1 × 50 mm) with the following parameters: injection volume: 10 µl, flow rate: 0.5 mL min⁻¹, column temperature: 30 °C, solvents: A (0.1% HCO_2H in ACN) and B (0.1% HCO_2H in H_2O), t = 0-0.5 min, 10% A; t = 0.5-5.5 min, $10 \rightarrow 90\%$ A then t = 5.5-6 min, 90%A. Areas recorded at 254 nm were ratioed with internal standard peak area (BHT). Remaining compound was ratioed with t = 0 peak area and the natural logarithm of the remaining compound ratio was plotted against time. Linear fit of the curve allowed us to determine $t_{1/2}$ for tested compound and microsomal intrinsic clearance (CLint, in µL min⁻¹ mg⁻¹ protein) was calculated using this equation as previously described:

$$\mathrm{CL_{int}} = \frac{0.693 \times (\mathrm{incubation\ volume})}{t_{1/2} \times (\mathrm{mg\ microsomal\ protein})}$$

In silico docking studies. Each protein (DYRK1A (PDB ID: 5AIK), CLK1 (PDB ID: 6RAA), CLK4 (PDB ID: 6FYV), haspin (PDB ID: 3IQ7)) has been setup and protonated (pH = 7) using MOE software (Molecular Operating Environment, 2022.2). The docking procedures were performed with GOLD software (version 2020.2.0) using the HERMES interface. GOLD scores have been optimized following variation of different parameters (solvated/unsolvated protein, co-crystallized structure origin, scoring and rescoring algorithms (Chemscore, Goldscore, PLP)).

The following parameters has showed the best correlations between biologics assays and fitness scoring: using protonated, unsolvated unminimized protein with a spherical site (10 Å radius) centered on the previously co-crystallized ligands, the GOLD template chemscore_kinase, Goldscore scoring and chemscore rescoring without using the "allow termination" option with a genetic algorithm (GA) search efficiency 100%.

Data were extracted as ".csv" extension and computed with excel.

Best and consistent results were extracted as "mol2" extension complexes and visualized with PyMOL (1.8.6.2) and MOE softwares to generate superposition, ligand interactions and images generation.

Data availability

The data used for the manuscript entitled "Design, synthesis, and structure-activity relationship studies of 6H-benzo[b] indeno[1,2-d]thiophen-6-one derivatives as DYRK1A/CLK1/ CLK4/haspin inhibitors" will be included in a ESI† file, available online on RSC Medicinal Chemistry web site.

Author contributions

Conceptualization: TL and RB. Formal analysis: TL and ME. Funding acquisition: TL and FH. Investigation: AF, AA, FH, JR, MA, VD, CVD, AM, MS, AE, T-NP, AB. Methodology: TL, RB and ME. Project administration: TL. Resources: TL, MLB, RT. Supervision: TL. Validation: TL and AA. Visualization: TL, VD, JR and FH. Writing - original draft: TL, VD and FH. Writing - review & editing: FH, ME, AF and TL.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

- 1 B. J. Druker, S. Tamura, E. Buchdunger, S. Ohno, G. M. Segal, S. Fanning, J. Zimmermann and N. B. Lydon, Nat. Med., 1996, 2, 561-566.
- 2 B. J. Druker, F. Guilhot, S. G. O'Brien, I. Gathmann, H. Kantarjian, N. Gattermann, M. W. N. Deininger, R. T. Silver, J. M. Goldman, R. M. Stone, F. Cervantes, A. Hochhaus, B. L. Powell, J. L. Gabrilove, P. Rousselot, J. Reiffers, J. J. Cornelissen, T. Hughes, H. Agis, T. Fischer, G. Verhoef, J. Shepherd, G. Saglio, A. Gratwohl, J. L. Nielsen, J. P. Radich, B. Simonsson, K. Taylor, M. Baccarani, C. So, L. Letvak and R. A. Larson, N. Engl. J. Med., 2006, 355, 2408-2417.
- 3 G. D. Demetri, M. von Mehren, C. D. Blanke, A. D. Van den Abbeele, B. Eisenberg, P. J. Roberts, M. C. Heinrich, D. A. Tuveson, S. Singer, M. Janicek, J. A. Fletcher, S. G. Silverman, S. L. Silberman, R. Capdeville, B. Kiese, B. Peng, S. Dimitrijevic, B. J. Druker, C. Corless, C. D. M. Fletcher and H. Joensuu, N. Engl. J. Med., 2002, 347, 472-480.
- 4 K. S. Bhullar, N. O. Lagarón, E. M. McGowan, I. Parmar, A. Jha, B. P. Hubbard and H. P. V. Rupasinghe, Mol. Cancer,
- 5 P. Cohen, D. Cross and P. A. Jänne, Nat. Rev. Drug Discovery, 2021, 20, 551-569.
- 6 R. Roskoski, Pharmacol. Res., 2023, 187, 106552.
- 7 H. Sung, J. Ferlay, R. L. Siegel, M. Laversanne, I. Soerjomataram, A. Jemal and F. Bray, Ca-Cancer J. Clin., 2021, 71, 209-249.
- 8 J. García-Cárceles, E. Caballero, C. Gil and A. Martínez, J. Med. Chem., 2022, 65, 935-954.
- 9 J. A. Keating and R. Striker, Rev. Med. Virol., 2012, 22, 166-181.
- 10 P. Le, E. Kunold, R. Macsics, K. Rox, M. C. Jennings, I. Ugur, M. Reinecke, D. Chaves-Moreno, M. W. Hackl, C. Fetzer, F. A. M. Mandl, J. Lehmann, V. S. Korotkov, S. M. Hacker, B. Kuster, I. Antes, D. H. Pieper, M. Rohde, W. M. Wuest, E. Medina and S. A. Sieber, Nat. Chem., 2020, 12, 145-158.
- 11 M. Bouhaddou, D. Memon, B. Meyer, K. M. White, V. V. Rezelj, M. C. Marrero, B. J. Polacco, J. E. Melnyk, S. Ulferts, R. M. Kaake, J. Batra, A. L. Richards, E. Stevenson, D. E. Gordon, A. Rojc, K. Obernier, J. M. Fabius, M. Soucheray, L. Miorin, E. Moreno, C. Koh, Q. D. Tran, A. Hardy, R. Robinot, T. Vallet, B. E. Nilsson-Payant, C. Hernandez-Armenta, A. Dunham, S. Weigang, J. Knerr, M. Modak, D. Quintero, Y. Zhou, A. Dugourd, A. Valdeolivas, T. Patil, Q. Li, R. Hüttenhain, M. Cakir, M. Muralidharan, M. Kim, G. Jang, B. Tutuncuoglu, J. Hiatt, J. Z. Guo, J. Xu, S. Bouhaddou, C. J. P. Mathy, A. Gaulton, E. J. Manners, E. Félix, Y. Shi, M. Goff, J. K. Lim, T. McBride, M. C. O'Neal, Y. Cai, J. C. J. Chang, D. J. Broadhurst, S. Klippsten, E. D. Wit, A. R. Leach, T. Kortemme, B. Shoichet, M. Ott, J. Saez-Rodriguez, B. R. tenOever, R. D. Mullins, E. R. Fischer, G. Kochs, R. Grosse, A. García-Sastre, M. Vignuzzi, J. R. Johnson, K. M. Shokat, D. L. Swaney, P. Beltrao and N. J. Krogan, Cell, 2020, 182, 685-712.e19.
- 12 C. Doerig, L. Meijer and J. C. Mottram, Trends Parasitol., 2002, 18, 366-371.

- 13 R. Y. Gaji, A. K. Sharp and A. M. Brown, Int. J. Parasitol., 2021, 51, 415-429.
- 14 J. Krämer, A. Bar-Or, T. J. Turner and H. Wiendl, Nat. Rev. Neurol., 2023, 19, 289-304.
- 15 F. Pagan, M. Hebron, E. H. Valadez, Y. Torres-Yaghi, X. Huang, R. R. Mills, B. M. Wilmarth, H. Howard, C. Dunn, A. Carlson, A. Lawler, S. L. Rogers, R. A. Falconer, J. Ahn, Z. Li and C. Moussa, J. Parkinson's Dis., 2016, 6, 503-517.
- 16 S. J. Mehdi, H. Rosas-Hernandez, E. Cuevas, S. M. Lantz, S. W. Barger, S. Sarkar, M. G. Paule, S. F. Ali and S. Z. Imam, Int. J. Mol. Sci., 2016, 17, 1585.
- 17 F. Fagiani, C. Lanni, M. Racchi and S. Govoni, Alzheimers Dement, 2020, 6, e12044.
- 18 S. Bagheri and A. A. Saboury, in Protein Kinase Inhibitors, ed. Md. I. Hassan and S. Noor, Academic Press, 2022, pp. 505-533.
- 19 E. Deboever, A. Fistrovich, C. Hulme and T. Dunckley, Int. J. Mol. Sci., 2022, 23, 9355.
- 20 Y. A. Liu, Q. Jin, Y. Zou, Q. Ding, S. Yan, Z. Wang, X. Hao, B. Nguyen, X. Zhang, J. Pan, T. Mo, K. Jacobsen, T. Lam, T. Y.-H. Wu, H. M. Petrassi, B. Bursulaya, M. DiDonato, W. P. Gordon, B. Liu, J. Baaten, R. Hill, V. Nguyen-Tran, M. Qiu, Y.-Q. Zhang, A. Kamireddy, S. Espinola, L. Deaton, S. Ha, G. Harb, Y. Jia, J. Li, W. Shen, A. M. Schumacher, K. Colman, R. Glynne, S. Pan, P. McNamara, B. Laffitte, S. Meeusen, V. Molteni and J. Loren, J. Med. Chem., 2020, 63, 2958-2973.
- 21 B. Pucelik, A. Barzowska, J. M. Dabrowski and A. Czarna, Int. J. Mol. Sci., 2021, 22, 9083.
- 22 T. Booiman, V. V. Loukachov, K. A. van Dort, A. B. van't Wout and N. A. Kootstra, PLoS One, 2015, 10, e0144229.
- 23 M. S. Strine, W. L. Cai, J. Wei, M. M. Alfajaro, R. B. Filler, S. B. Biering, S. Sarnik, R. D. Chow, A. Patil, K. S. Cervantes, C. K. Collings, P. C. DeWeirdt, R. E. Hanna, K. Schofield, C. Hulme, S. Konermann, J. G. Doench, P. D. Hsu, C. Kadoch, Q. Yan and C. B. Wilen, PLoS Biol., 2023, 21, e3002097.
- 24 B. Smith, F. Medda, V. Gokhale, T. Dunckley and C. Hulme, ACS Chem. Neurosci., 2012, 3, 857-872.
- 25 S. Stotani, F. Giordanetto and F. Medda, Future Med. Chem., 2016, 8, 681-696.
- 26 Y. S. Ryu, S. Y. Park, M.-S. Jung, S.-H. Yoon, M.-Y. Kwen, S.-Y. Lee, S.-H. Choi, C. Radnaabazar, M.-K. Kim, H. Kim, K. Kim, W.-J. Song and S.-H. Chung, J. Neurochem., 2010, 115, 574-584.
- 27 D. B. Jarhad, K. K. Mashelkar, H.-R. Kim, M. Noh and L. S. Jeong, J. Med. Chem., 2018, 61, 9791–9810.
- 28 M. F. Lindberg, E. Deau, J. Arfwedson, N. George, P. George, P. Alfonso, A. Corrionero and L. Meijer, J. Med. Chem., 2023, 66, 4106-4130.
- 29 W. Stensen, U. Rothweiler, R. A. Engh, M. R. Stasko, I. Bederman, A. C. S. Costa, A. Fugelli and J. S. M. Svendsen, Pharmaceuticals, 2021, 14, 1170.
- 30 S. Gourdain, J. Dairou, C. Denhez, L. C. Bui, F. Rodrigues-Lima, N. Janel, J. M. Delabar, K. Cariou and R. H. Dodd, J. Med. Chem., 2013, 56, 9569-9585.
- 31 H. Falke, A. Chaikuad, A. Becker, N. Loaëc, O. Lozach, S. Abu Jhaisha, W. Becker, P. G. Jones, L. Preu, K. Baumann, S.

- Knapp, L. Meijer and C. Kunick, J. Med. Chem., 2015, 58, 3131-3143.
- 32 E. Deau, M. F. Lindberg, F. Miege, D. Roche, N. George, P. George, A. Krämer, S. Knapp and L. Meijer, J. Med. Chem., 2023, 66, 10694-10714.
- 33 M. W. Karaman, S. Herrgard, D. K. Treiber, P. Gallant, C. E. Atteridge, B. T. Campbell, K. W. Chan, P. Ciceri, M. I. Davis, P. T. Edeen, R. Faraoni, M. Floyd, J. P. Hunt, D. J. Lockhart, Z. V. Milanov, M. J. Morrison, G. Pallares, H. K. Patel, S. Pritchard, L. M. Wodicka and P. P. Zarrinkar, Nat. Biotechnol., 2008, 26, 127-132.
- M. I. Davis, J. P. Hunt, S. Herrgard, P. Ciceri, L. M. Wodicka, G. Pallares, M. Hocker, D. K. Treiber and P. P. Zarrinkar, Nat. Biotechnol., 2011, 29, 1046-1051.
- 35 C. Neagoie, E. Vedrenne, F. Buron, J.-Y. Mérour, S. Rosca, S. Bourg, O. Lozach, L. Meijer, B. Baldeyrou, A. Lansiaux and S. Routier, Eur. J. Med. Chem., 2012, 49, 379-396.
- C. Schmitt, P. Miralinaghi, M. Mariano, R. W. Hartmann and M. Engel, ACS Med. Chem. Lett., 2014, 5, 963-967.
- The para-hydroxy benzothiophenyl methyl ketone 1-(5hydroxy-1-benzothiophen-2-yl)ethan-1-one, with a methyl group instead of the aryl one, was also reported (see ref. 36) as an efficient DYRK1A/DYRK1B/CLK1 inhibitor, with low IC₅₀ values (200 nM/100 nM/60 nM, respectively).
- 38 S. Pérez-Silanes, J. Martínez-Esparza, A. M. Oficialdegui, H. Villanueva, L. Orúas and A. Monge, J. Heterocyclic Chem., 2001, 38, 1025-1030.
- 39 D.-T. D. Tang, K. D. Collins and F. Glorius, J. Am. Chem. Soc., 2013, 135, 7450-7453.
- 40 B. Février, G. Dupas, J. Bourguignon and G. Quéguiner, J. Heterocyclic Chem., 1993, 30, 1085-1088.
- 41 N. J. Taylor, E. Emer, S. Preshlock, M. Schedler, M. Tredwell, S. Verhoog, J. Mercier, C. Genicot and V. Gouverneur, J. Am. Chem. Soc., 2017, 139, 8267-8276.
- 42 I. Cerminara, L. Chiummiento, M. Funicello, A. Guarnaccio and P. Lupattelli, Pharmaceuticals, 2012, 5, 297-316.
- A. Faouzi, A. Arnaud, A. Bancet, C. Barette, J. Preto, C. V. Do, L. P. Jordheim, Z. Bousfiha, T. T. B. Nguyen, M. Verrière, A. Farce, M.-O. Fauvarque, R. Barret and T. Lomberget, Eur. J. Med. Chem., 2021, 215, 113275.
- 44 B. A. Hathaway, K. L. White and M. E. McGill, Synth. Commun., 2007, 37, 3855-3860.
- 45 A. Whyte, M. E. Olson and M. Lautens, Org. Lett., 2018, 20, 345-348.
- 46 S. Neufeind, N. Hülsken, J.-M. Neudörfl, N. Schlörer and H.-G. Schmalz, Chem. - Eur. J., 2011, 17, 2633-2641.
- 47 N. Marquise, P. J. Harford, F. Chevallier, T. Roisnel, A. E. H. Wheatley, P. C. Gros and F. Mongin, Tetrahedron Lett., 2013, 54, 3154-3157.
- 48 C. Schmitt, D. Kail, M. Mariano, M. Empting, N. Weber, T. Paul, R. W. Hartmann and M. Engel, PLoS One, 2014, 9, e87851.
- 49 Q. Zhou, A. F. Phoa, R. H. Abbassi, M. Hoque, T. A. Reekie, J. S. Font, R. M. Ryan, B. W. Stringer, B. W. Day, T. G. Johns, L. Munoz and M. Kassiou, J. Med. Chem., 2017, 60, 2052-2070.

- 50 Y. T. AlNajjar, M. Gabr, A. K. ElHady, M. Salah, G. Wilms, A. H. Abadi, W. Becker, M. Abdel-Halim and M. Engel, Eur. J. Med. Chem., 2022, 227, 113911.
- 51 G. A. Patani and E. J. LaVoie, Chem. Rev., 1996, 96, 3147-3176.
- 52 N. A. Meanwell, in *Tactics in Contemporary Drug Design*, ed. N. A. Meanwell, Springer, Berlin, Heidelberg, 2015, pp. 283-
- 53 B. S. Jayashree, P. S. Nikhil and S. Paul, Med. Chem., 2022, 18, 915-925.
- 54 S. Avula, X. Peng, X. Lang, M. Tortorella, B. Josselin, S. Bach, S. Bourg, P. Bonnet, F. Buron, S. Ruchaud, S. Routier and C. Neagoie, J. Enzyme Inhib. Med. Chem., 2022, 37, 1632-1650.
- 55 M. Defois, B. Josselin, P. Brindeau, A. Krämer, S. Knapp, F. Anizon, F. Giraud, S. Ruchaud and P. Moreau, Bioorg. Med. Chem., 2024, 100, 117619.
- 56 L. Garuti, M. Roberti and G. Bottegoni, Curr. Med. Chem., 2015, 22, 695-712.
- 57 O. V. Ancker, M. Krüger, M. Wehland, M. Infanger and D. Grimm, Int. J. Mol. Sci., 2020, 21, 10.
- 58 M. L. Gild, V. H. M. Tsang, R. J. Clifton-Bligh and B. G. Robinson, Nat. Rev. Endocrinol., 2021, 17, 225-234.
- 59 E. Wang, J. M. B. Pineda, W. J. Kim, S. Chen, J. Bourcier, M. Stahl, S. J. Hogg, J. P. Bewersdorf, C. Han, M. E. Singer, D. Cui, C. E. Erickson, S. M. Tittley, A. V. Penson, K. Knorr, R. F. Stanley, J. Rahman, G. Krishnamoorthy, J. A. Fagin, E. Creger, E. McMillan, C.-C. Mak, M. Jarvis, C. Bossard, D. M. Beaupre, R. K. Bradley and O. Abdel-Wahab, Cancer Cell, 2023, 41, 164-180.e8.
- 60 N. Babu, S. M. Pinto, M. Biswas, T. Subbannayya, M. Rajappa, S. V. Mohan, J. Advani, P. Rajagopalan, G. Sathe, N. Syed, V. D. Radhakrishna, O. Muthusamy, S. Navani, R. V. Kumar, G. Gopisetty, T. Rajkumar, P. Radhakrishnan, S. Thiyagarajan, A. Pandey, H. Gowda, P. Majumder and A. Chatterjee, *Gastric Cancer*, 2020, 23, 796-810.
- 61 A. K. ElHady, D. S. El-Gamil, A. H. Abadi, M. Abdel-Halim and M. Engel, Med. Res. Rev., 2023, 43, 343-398.
- 62 P. Martín Moyano, V. Němec and K. Paruch, Int. J. Mol. Sci., 2020, 21, 7549.
- 63 M. Song, L. Pang, M. Zhang, Y. Qu, K. V. Laster and Z. Dong, Signal Transduction Targeted Ther., 2023, 8, 1-25.
- 64 G. D. A. Guardia, B. R. Correa, P. R. Araujo, M. Qiao, S. Burns, L. O. F. Penalva and P. A. F. Galante, npj Genomic Med., 2020, 5, 1-12.
- 65 N. G. Amoussou, A. Bigot, C. Roussakis and J.-M. H. Robert, Drug Discovery Today, 2018, 23, 409-415.
- 66 A. Recasens, S. J. Humphrey, M. Ellis, M. Hoque, R. H. Abbassi, B. Chen, M. Longworth, E. J. Needham, D. E. James, T. G. Johns, B. W. Day, M. Kassiou, P. Yang and L. Munoz, Cell Death Discovery, 2021, 7, 1–16.
- 67 A. Thakur, C. Faujdar, R. Sharma, S. Sharma, B. Malik, K. Nepali and J. P. Liou, J. Med. Chem., 2022, 65, 8596-8685.
- 68 N. Pozo, C. Zahonero, P. Fernández, J. M. Liñares, A. Ayuso, M. Hagiwara, A. Pérez, J. R. Ricoy, A. Hernández-Laín, J. M.

- Sepúlveda and P. Sánchez-Gómez, J. Clin. Invest., 2013, 123, 2475-2487.
- 69 B. Chen, D. McCuaig-Walton, S. Tan, A. P. Montgomery, B. W. Day, M. Kassiou, L. Munoz and A. Recasens, Int. J. Mol. Sci., 2021, 22, 4011.
- 70 M. Tarpley, H. O. Oladapo, D. Strepay, T. B. Caligan, L. Chdid, H. Shehata, J. R. Roques, R. Thomas, C. P. Laudeman, R. U. Onyenwoke, D. B. Darr and K. P. Williams, Eur. J. Pharm. Sci., 2021, 162, 105821.
- 71 H. Liu, Q. Sun, S. Chen, L. Chen, W. Jia, J. Zhao and X. Sun, Cancer Med., 2021, 10, 6416-6427.
- 72 X. Xu, O. Liu, C. Zhang, S. Ren, L. Xu, Z. Zhao, H. Dou, P. Li, X. Zhang, Y. Gong and C. Shao, Cell Death Dis., 2019, 10,
- 73 S. Tan, J. Zhao and P. Wang, *Int. J. Oncol.*, 2023, **63**, 1–14.
- 74 Molecular Operating Environment (MOE), 2022.02 Chemical Computing Group ULC, 910-1010 Sherbrooke St. W., Montreal, QC H3A 2R7, Canada, 2023.
- 75 G. Jones, P. Willett, R. C. Glen, A. R. Leach and R. Taylor, J. Mol. Biol., 1997, 267, 727-748.
- 76 A. Pathak, A. Rohilla, T. Gupta, M. J. Akhtar, M. R. Haider, K. Sharma, K. Haider and M. S. Yar, Eur. J. Med. Chem., 2018, 158, 559-592.
- 77 S. H. Henderson, F. Sorrell, J. Bennett, M. T. Hanley, S. Robinson, I. H. Navratilova, J. M. Elkins and S. E. Ward, ACS Med. Chem. Lett., 2020, 11, 1620-1626.
- 78 A. K. Ghosh and M. Brindisi, J. Med. Chem., 2015, 58, 2895-2940.
- 79 J. M. Ferriz and J. Vinsova, Curr. Pharm. Des., 2010, 16, 2033-2052.
- 80 S. S. Dhareshwar and V. J. Stella, in Prodrugs: Challenges and Rewards Part 1, ed. V. J. Stella, R. T. Borchardt, M. J. Hageman, R. Oliyai, H. Maag and J. W. Tilley, Springer, New York, NY, 2007, pp. 731-799.
- 81 A. B. Montaser, J. Järvinen, S. Löffler, J. Huttunen, S. Auriola, M. Lehtonen, A. Jalkanen and K. M. Huttunen, ACS Chem. Neurosci., 2020, 11, 4301-4315.
- 82 R. Mahato, W. Tai and K. Cheng, Adv. Drug Delivery Rev., 2011, 63, 659-670.
- 83 J. Rautio, N. A. Meanwell, L. Di and M. J. Hageman, Nat. Rev. Drug Discovery, 2018, 17, 559-587.
- 84 S. Jaracz, J. Chen, L. V. Kuznetsova and I. Ojima, Bioorg. Med. Chem., 2005, 13, 5043-5054.
- F. Kratz, I. A. Müller, C. Ryppa and A. Warnecke, 85 ChemMedChem, 2008, 3, 20-53.
- 86 H. E. Gottlieb, V. Kotlyar and A. Nudelman, J. Org. Chem., 1997, 62, 7512-7515.
- 87 A. F. Burchat, J. M. Chong and N. Nielsen, J. Organomet. Chem., 1997, 542, 281-283.
- 88 H. Konishi, H. Tanaka and K. Manabe, Org. Lett., 2017, 19, 1578-1581.
- 89 A. Boelke, E. Lork and B. J. Nachtsheim, Chem. Eur. J., 2018, 24, 18653-18657.
- 90 E. Fillion, V. É. Trépanier, J. J. Heikkinen, A. A. Remorova, R. J. Carson, J. M. Goll and A. Seed, Organometallics, 2009, 28, 3518-3531.

- 91 J. Takaya, K. Sangu and N. Iwasawa, *Angew. Chem.*, 2009, **121**, 7224–7227.
- 92 T. Mosmann, J. Immunol. Methods, 1983, 65, 55-63.
- 93 J. Tan, H. Sivaram and H. V. Huynh, *Appl. Organomet. Chem.*, 2018, 32, e4441.
- 94 C. Doebelin, I. Bertin, S. Schneider, M. Schmitt, J.-J. Bourguignon, C. Ancel, V. Simonneaux, F. Simonin and F. Bihel, *ChemMedChem*, 2016, **11**, 2147–2154.
- 95 S. Keller, Y. C. Ong, Y. Lin, K. Cariou and G. Gasser, J. Organomet. Chem., 2020, 906, 121059.