Structural Investigation of Cycloheptathiophene-3-carboxamide Derivatives
Targeting Influenza Virus Polymerase Assembly

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TITLE RUNNING HEAD: Cycloheptathiophene derivatives with anti-influenza activity.

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Abbreviations: CC\textsubscript{50}, concentration that causes a decrease of cell viability of 50%; Flu, influenza virus; FluA, influenza A virus; FluB, influenza B virus; MDCK, Mardin-Darby canine kidney; NP, nucleoprotein; PA, polymerase acidic protein; PB1, polymerase basic protein 1; PB2, polymerase basic protein 2; PPI, protein-protein interaction; PRA, plaque reduction assays; RBV, Ribavirin; RdRP, RNA-dependent RNA polymerase; RNP, ribonucleoprotein.

ABSTRACT
The limited number of drug classes licensed for treatment of influenza virus (Flu), together with the continuous emergence of viral variants and drug resistant mutants, highlight the urgent need to find antivirals with novel mechanisms of action. In this context, the viral RNA-dependent RNA polymerase (RdRP) subunits assembly has emerged as an attractive target. Starting from a cycloheptathiophene-3-carboxamide derivative recently identified by us for its ability to disrupt the interaction between the PA and PB1 subunits of RdRP, we have designed and synthesized a series of analogues. Their biological evaluation led to the identification of more potent protein-protein interaction inhibitors, endowed with antiviral activity that also encompassed a number of clinical isolates of FluA, including an oseltamivir-resistant strain, and FluB, without showing appreciable toxicity. From this study, the cycloheptathiophene-3-carboxamide scaffold emerged as particularly suitable to impart anti-Flu activity.

INTRODUCTION
The discovery of novel antiviral therapies\textsuperscript{1} and the continuing development of annual vaccines\textsuperscript{2} have not yet led to an adequate treatment for influenza virus (Flu\textsuperscript{a}), an important pathogen responsible for both yearly seasonal epidemics and more extensive global pandemics. This issue was clearly evident during the unexpected emergence of the 2009 H1N1 pandemic strain by the reassortment of genes from human, pig, and bird's H1N1 viruses.\textsuperscript{3} This last pandemic, together with the on-going circulation of highly pathogenic avian H5N1 strains and the recent emergence of the...
H7N9 virus, a new reassortant of avian origin isolated in China and associated with severe respiratory disease with 40% of mortality, which could potentially adapt for human-to-human transmission, highlighted the vulnerability of the world population to novel Flu strains. Although vaccination remains the main prophylactic strategy for controlling Flu infection, during the lagging time needed to produce a new vaccine and even during typical epidemic years, since vaccination does not prevent completely Flu infection, our only weapon against pandemic Flu are antivirals. Currently, only two classes of drugs have been approved by FDA for the treatment of Flu: the neuraminidase inhibitors oseltamivir and zanamivir, that are active on both influenza A (FluA) and influenza B (FluB) viruses, and the M2 channel blockers amantadine and rimantadine, whose spectrum of action is limited to FluA. Since Flu viruses have a high mutation rate, a major problem with both classes of drugs is the emergence of drug-resistant strains. Clearly, next-generation antivirals are needed to efficiently combat Flu, preferably with an innovative mechanism of action. The viral RNA-dependent RNA polymerase (RdRP) provides an attractive target given its functional essentiality for viral replication and involvement in virus pathogenicity. RdRP could be ideal for the development of new antivirals, since it is highly conserved among FluA, B, and C while no homologue has been found in mammalian cells. RdRP is a complex of three subunits, polymerase acidic protein (PA), polymerase basic protein 1 (PB1), and polymerase basic protein 2 (PB2), which are responsible for both transcription and replication. The assembly of the three subunits into functional viral RdRP is an essential step for influenza virus RNA synthesis and virus replication. Thus, the interference with its correct assembly through protein-protein interaction (PPI) inhibitors represents an attractive strategy to inhibit this enzyme. Although very challenging, the feasibility of such an approach has been demonstrated by the identification of antiviral peptides able to inhibit the PA-PB1 interaction. The recent publication of two crystallographic structures of a truncated form of PA bound to a PB1-derived peptide has shown that relatively few residues drive the binding of PB1 to PA, suggesting the potential for small molecule-mediated inhibition. The proof-of-principle that the PA-PB1 interaction can be indeed
disrupted also by small molecular-weight compounds was recently provided by us and few other authors. In our SBDD approach, an in silico screening of 3 million small molecules from the ZINC database, performed using one of the available crystal structures, led to the identification of 32 virtual hits which were then evaluated in vitro for their ability to disrupt the PA-PB1 interaction. Five of them inhibited this interaction specifically and in a dose-dependent manner with IC \(_{50}\) values in the micromolar range, making all of them worthy of further investigation.

In the present study, we attempted the structural optimization of thiophene-3-carboxamide derivative 1 (Figure 1, compound 10 in reference 31). This compound was able to disrupt the PA-PB1 interaction in vitro with an IC \(_{50}\) of 90.7 µM and, even though it exhibited antiviral activity against FluA in infected cells at EC \(_{50}\) values slightly higher than 100 µM, its peculiar mechanism of action, coupled with the lack of cytotoxicity (CC \(_{50}\) > 250 µM) evaluated in two cell lines (Mardin-Darby canine kidney (MDCK) and HEK 293T), made this compound a valid starting point. In an attempt to improve the ability to disrupt the PA-PB1 interaction and achieve a better anti-Flu activity, while maintaining the lack of toxicity, a number of structural modifications were undertaken synthesizing a series of analogues (compounds 2-36 in Table 1). Herein we report on their design, synthesis, and biological evaluation.

**DESIGN OF THIOPHENE-3-CARBOXAMIDE DERIVATIVES**

Compound 1 is made up of a tetrahydrocycloheptathiophene ring bearing at both the C-2 and C-3 positions an amide moiety functionalized with an aromatic ring (Figure 1). The attention was mainly focused on modifying the \(\alpha\)-fluorophenyl ring placed at the C-2 position, due to the higher synthetic accessibility. In particular, following the classical medicinal chemistry strategy, the \(\alpha\)-fluoro atom was eliminated (compound 2), shifted as in its positional isomers (compounds 3 and 4) as well as replaced by chlorine atom (compounds 5 and 6); dihalogen derivatives (compounds 7 and 8) were also prepared. A cyclohexyl ring replaced the phenyl group in derivative 9. Then, the phenyl/cyclohexyl ring was spaced by inserting one or two methylenic units (compounds 10-16).
Additional derivatives were synthesized following the suggestions of a computational study performed using the same method that recently led us to identify a number of inhibitors of the PA/PB1 binding.\textsuperscript{31} The FLAP (Fingerprints for Ligands and Proteins) structure-based virtual screening algorithm was recently used to identify a number of inhibitors of the PA/PB1 binding, using the x-ray crystallographic structure of the PA/PB1 complex\textsuperscript{28} as a template.

Additional derivatives were synthesized following the suggestions of a computational study performed using the Fingerprints for Ligands and Proteins (FLAP) algorithm. This method recently led us to identify a number of inhibitors of the PA/PB1 binding,\textsuperscript{31} using the x-ray crystallographic structure of the PA/PB1 complex\textsuperscript{28} as a template. Although FLAP is not a classical docking procedure based on energy minimization, it allows to evaluate hypotheses on the binding mode of the screened compounds looking for the best overlap of the GRID Molecular Interaction Fields (MIFs), calculated for the protein cavity and for the ligand.\textsuperscript{35-37} Hydrophobic, hydrophilic and hydrogen-bond donor and acceptor interactions are considered. Since GRID MIFs are energy related, a high similarity between the MIFs of the protein and the ligands indicates an energy favored binding mode.

Our previous study revealed the importance of hydrophobic interactions in the ligand-PA recognition process.\textsuperscript{31} The green spots in Figure 2-A represent the hydrophobic regions in the PA cavity generated by GRID Force Field.\textsuperscript{38} The presence of those regions in the PA cavity is in agreement with the findings of Liu \textit{et al.}\textsuperscript{39} who described the existence of three hydrophobic pockets. Indeed, one hydrophobic pocket is generated by W706 and P411, and is responsible for the binding of P5 from PB1. The second hydrophobic pocket is due to P710 and L666 interactions, and it is responsible for the binding of F9 from PB1. Finally, L640, V636, M595, and W619 are responsible for the third hydrophobic pocket, where L8 of PB1 is located. An additional hydrophobic spot is located in the middle of the cavity and mainly generated by the aliphatic chain of E623 and the protein backbone. The most favourable FLAP docking pose in the PA cavity for compound 1, is shown in Figure 2-B. Based on our model, compound 1 interacts with the first and
the second pockets and with the additional central hydrophobic region. From Figure 2-B one can reason that, in order to optimize the hydrophobic interactions to better fit the second pocket defined by Liu et al., the o-fluorophenyl ring at the C-2 position of compound 1 could be replaced with a bulkier aromatic substituent. In agreement with this hypothesis, a series of bicyclic heteroaromatic derivatives were designed looking for the best compromise between solubility and lipophilicity, according to the predicted values calculated using VolSurf+ and the synthetic accessibility. Among the selected compounds, we synthesized 17 and 18 as first examples of such derivatives; their best poses are reported in Figures 2-C and 2-D. Compounds 1, 17, and 18 display a similar orientation, with the tetrahydrocycloheptathiophene moiety being oriented towards the W706 PA residue in the first pocket likely involving π–π interactions. The substituent in C-2 position is located in the second pocket, while the substituent in C-3 position fits the central hydrophobic spot. In addition, it must be noticed that, according to the our modeling studies, all three compounds might be stabilized by a hydrogen bond between the oxygen of the C-2 amide group and the PA residue K643.

To conclusively determine the role that the simultaneous presence of both the aromatic rings at C-2 and C-3 positions plays on the biological activity, we synthesized the 2-amino derivative 19, which lacks the o-fluorobenzoyl moiety, and the primary amide 20, which lacks the C-3 pyridine ring. The ester and acid derivatives 21 and 22, analogues of 20, were also synthesized together with additional ethyl esters 23-26 and the corresponding acids 27-30, characterized by various substituents at the C-2 position.

Few modifications involved the cycloheptane ring, whose size was reduced to cyclohexane and cyclopentane as in compounds 31 and 32, the direct analogues of 1, as well as in the C-3 variously functionalized derivatives 33-36. However, the increased toxicity, especially of the cyclohexane derivatives, has discouraged the synthesis of further analogues.
The synthesis of 2-[(substituted)amino]-N-(2-pyridinyl)thiophene-3-carboxamide derivatives 1-18, 31, and 32 was accomplished, as outlined in Scheme 1, by applying the two-step Gewald synthesis.42,43 Thus, a first Knoevenagel condensation of various cycloalkyl ketones with 2-cyano-N-pyridin-2-ylacetamide44 gave \( \alpha,\beta \)-unsaturated nitriles. These intermediates were used without isolation in the successive cyclization step, performed in the presence of sulphur and \( N,N \)-diethyleamine in EtOH, to give derivatives 19, 37, and 38. The target compounds 1-16, 31, and 32 were then obtained by a coupling reaction of these intermediates with the appropriate acyl chlorides in pyridine. Amide bond formation in derivatives 17 and 18 was carried out through an alternative procedure, by reacting intermediate 19 with quinolin-6-ylacetic acid and (3-methoxy-1-benzothien-2-yl)acetic acid, respectively, in THF in the presence of 4-(4,6-dimethoxy-(1,3,5)-triazin-2-yl)-4-methyl-morpholinium chloride (DMTMM)45 as activating agent.

The starting materials for the preparation of the remaining derivatives were compounds 39-41,46 42,47 and 43,42 that reacting with selected benzoyl chlorides gave thiophene-3-carboxamides 20, 33,48 and 3448 and ethyl thiophene-3-carboxylates 21, 23, 24, 25,47 26, and 35,49 as shown in Scheme 2. The thiophene-3-carboxylic acids 22, 27-30, and 36 were then prepared by basic hydrolysis, starting from the corresponding ethyl esters.

RESULTS AND DISCUSSION

We started the study synthesizing and testing compound 1. The in-house synthesized 1 displayed biological activity comparable to that reported for the commercial derivative (compound 10 in reference 31). Indeed, it was endowed with a slightly lower PA-PB1 interaction inhibitory activity (IC\(_{50} = 145 \mu M\)) and a slightly higher anti-FluA activity in MDCK cells (EC\(_{50} = 90 \mu M\)); the in-house synthesized 1 was used as comparative compound in all successive studies.

The whole set of derivatives were evaluated for their ability to inhibit the physical interaction between PA and PB1 subunits by ELISA assays, including the PB1(1-15)-Tat peptide\(^{26}\) as a positive control. This peptide, which contains a synthetic PB1-derived peptide (amino acids 1–15) fused to
the translocating domain of HIV Tat protein, inhibited the PA–PB1 interaction with an apparent IC$_{50}$ of 35 μM (Table 1).

In parallel, for all the synthesized compounds the antiviral activity was tested in FluA virus-infected MDCK cells by plaque reduction assays (PRA) with the A/PR/8/34 (PR8) strain. Ribavirin (RBV), a known inhibitor of RNA viruses polymerase,$^{30}$ was included as a positive control, exhibiting an EC$_{50}$ of 8 μM (Table 1).

To exclude that the observed antiviral activities could be due to toxic effects in the target cells, all the synthesized compounds were tested by MTT assays in two cell lines, i.e., MDCK and HEK 293T (Table 1). RBV, included again as a reference compound, showed a CC$_{50}$ value > 250 μM in both cell lines, as previously reported.$^{51,52}$

Looking at the activities shown in Table 1, it clearly appears that in some cases, such as in compounds 4-6 and 17-19, the structural modifications improved the ability of the analogues to inhibit the PA–PB1 interaction. In particular, compounds 6 and 19 were the most potent with IC$_{50}$ values of 32 and 35 μM, superimposable to that of the reference peptide. In addition, the 2-bycyclic derivatives 17 and 18, designed to improve the inhibitory efficiency of the hit 1 by increasing the hydrophobic interactions, defined by GRID MIFs, indeed proved to be better inhibitors, especially 17, which exhibited an inhibitory activity 3-fold higher than that of compound 1. This finding can also be considered a validation of the suggested binding pose for compound 1. According to the docking studies FLAP docking pose reported in Figure 2, the different inhibitory activity among 1, 17, and 18 does not seem to correspond to a different binding mode of the compounds. However, considering that the three structures differ in the substituent at the C-2 position only, and that 17 possesses the most hydrophobic substituent in that position, this suggests that a stronger hydrophobic interaction could be the reason for a more difficult displacement of the compound, resulting in an increased activity.

Since the -FLAP- structure-based approach proved to be successful to retrieve and optimize ligand-protein complexes,$^{31,36}$ and in order to make a comparison with the binding modes hypothesized for
the other PA/PB1 inhibitors, we inspected the possible FLAP docking poses for the most active compounds, 6 and 19, in the PA cavity; results are shown in Figure 3. While for compounds 1, 17, and 18 reported in Figure 2 the most favorable poses were obtained upon interaction with the PA X-ray conformation (i.e. structure 3CM8 after removal of PB1, thus in the most favorable pose for PB1 binding), the docking of 6 in the same cavity resulted to be unfavorable due to a steric hindrance between the p-chloro and the P710 residue defining the second hydrophobic pocket. However, the analysis of the flexibility of P710 based on the dynamic studies previously reported\(^{31}\) showed that this residue can rotate when the PA-PB1 complex is not formed. At the same time, W706, which is not directly involved in PB1 binding but represents the bottom of the second hydrophobic cavity, can freely rotate to further enlarge this sub-pocket. Using a more relaxed snapshot of the PA structure, having the P710 and of W706 rotated to enlarge the second pocket (see Figure 3-A), 6 results to retain a strong π-π interaction with W706 and the p-chlorophenyl group of derivative 6 can fit the enlarged second pocket (Figure 3-B). Compound 6 can be further stabilized by R663 or K643 through H-bonds. A possible explanation of the high activity of 6 can be due to the presence of the p-chloro substituent that may induce a change in the position of residue P710. In this new position, P710 may interfere with the PA-PB1 interaction. Although an in-deep Molecular Dynamic investigation was not performed, this study led to hypothesize that conformational changes in the second hydrophobic pocket might play a role in the stabilization of the PA-ligand complex.

The high PA-PB1 inhibitory activity found for the 2-amino derivative 19 represents an intriguing result, showing that the presence of a hydrophobic moiety in the C-2 position is even not essential for activity. Concerning the possible PA-19 interaction, the structural features of 19 do not allow the simultaneous binding to the three hydrophobic regions observed for compounds 1, 17, and 18. However, despite the analogy with the other docked compounds would suggest that 19 could occupy the first and the central hydrophobic pocket, the docking pose for this compound actually results to be flipped, with the pyridine group being located in the second pocket (Figure 3-C).
support this hypothesis, binding energies for compounds 6 and 19 displaying similar activity despite structural differences, should be comparable. Indeed, the binding energies for the FLAP docked poses, evaluated using the GRID package, differ for 5 Kcal/mole. This behavior seems to suggest that the interaction with the second pocket rather than with the central pocket should be investigated to improve activity. PA residues that result to be involved in the binding of 19 are W706, I666, and P710. A H-bond with K643 could also occur. For the weak PA-PBI inhibitors 2, 4, and 5, the FLAP binding poses have been also inspected (Figure S1). Compounds 2 and 4 resulted to be similarly oriented, while for compound 5 the chlorine atom in ortho position of the phenyl group seems to induce a slightly different binding mode with weaker hydrophobic interaction, in agreement with the Elisa ELISA data.

All the compounds able to inhibit PA-PBI interaction were also active in inhibiting virus growth, with EC\textsubscript{50} values ranging from 18 μM for compound 6 to 61 μM for compound 18. In addition, many of the compounds synthesized in this study were surprisingly endowed with antiviral activity in the micromolar range and at nontoxic concentrations, although they were inactive in vitro as PA-PBI inhibitors. Examining all the anti-influenza data reported in Table 1, some clues emerged. The cycloheptane ring of compound 1 cannot be replaced by smaller rings such as cyclohexane and cyclopentane; indeed, both derivatives 31 and 32 were inactive while displaying some cytotoxicity in 293T cells, more evident for the cyclohexane derivative 31 (CC\textsubscript{50} = 60 μM). The unsuitability of smaller rings was also confirmed by the inactivity of the C-3 primary amides 33 and 34 and ester 35. Once again, the cyclohexane derivative 33 showed a certain toxicity on both cell lines, with CC\textsubscript{50} = 31 μM in 293T cells.

Maintaining the N-pyridinyl-cycloheptathiophene-3-carboxamide, the o-fluorophenyl ring of compound 1 has been widely modified. The fluorine atom deletion (compound 2) as well as its shifting to the meta position (compound 3) were detrimental, while the p-fluoro derivative 4 was characterized by an increase in the inhibition of Flu replication (EC\textsubscript{50} = 58 μM). The replacement of
the fluorine atom with a chlorine was productive at the *ortho* position as in compound 5 (EC$_{50}$ = 39 µM) but above all at the *para* position; indeed, compound 6 emerged as one of the most potent (EC$_{50}$ = 18 µM) in agreement with the PA-PB1 inhibitory activity. The addition of another halogen atom permitted the activity to be maintained as in derivatives 7 and 8. The presence of the cyclohexane ring at the C-2 position improved the activity giving compound 9 with EC$_{50}$ = 20 µM, which was, however, endowed with a slight cytotoxicity (CC$_{50}$ = 180 µM). Excellent antiviral activity was obtained inserting a monomethylene or dimethylene chain between the C-2 amide moiety and the phenyl ring. Indeed, methylphenyl derivatives 10, 11, and 12, as well as the ethylphenyl analogues 13, 15, and 16, showed EC$_{50}$ values ranging from 16 µM to 21 µM. On the contrary, spacing the cyclohexyl moiety from the C-2 position was deleterious, as 14 was inactive. The addition of a further aromatic ring at the C-2 position as in compounds 17 and 18 imparted a medium activity against virus replication, as expected by their anti-PA-PB1 activity. Notably, the deletion of the aromatic substituent from the C-2 position, as in the amino derivative 19, permitted to maintain a very good anti-Flu activity with an EC$_{50}$ value of 26 µM, similar to that observed in the ELISA assay.

When the 2-pyridine ring was deleted placing at the C-3 position a primary amide function, the antiviral activity disappeared (compound 20) and the same behaviour was shown by cyclopentane and cyclohexane analogues 33 and 34. On the other hand, all the ethyl cycloheptathiophene-3-carboxylates 21, and 23-26, as well as the corresponding acids 22, and 27-30 possessed antiviral activity with EC$_{50}$ values ranging from 43 µM to 95 µM. In general, the acid derivatives displayed a better activity than the ester analogues, with the p-chlorophenyl derivative 29 emerging once again as the best compound, with an EC$_{50}$ value of 43 µM.

Among all the synthesized compounds, p-chloro (compound 6), 2-amino (compound 19), and bicyclic derivatives (17 and 18), which exhibited the best inhibitory activity against both the PA-PB1 interaction and viral growth, were selected for further investigations including RBV as a control.
First we evaluated the effects of the compounds in virus yield assays, where all the them showed good antiviral activity (Table 2). Then, we investigated whether their ability to disrupt the PA-PB1 interaction in vitro correlated with the ability to interfere with the catalytic activity of FluA RdRP in a cellular context. To this end, a minireplicon assay was performed. 293T cells were cotransfected in the presence of the test compounds or DMSO with plasmids for the expression of influenza nucleoprotein (NP), PA, PB1, and PB2 proteins and the firefly luciferase RNA in negative-sense orientation, flanked by the noncoding regions of Flu A/WSN/33 segment 8. The expression of the firefly reporter gene indicates that a negative-sense RNA is synthesized and is reconstituted intracellularly into functional ribonucleoprotein (RNP) in which all four NP, PA, PB1, and PB2 proteins are coexpressed and interact with each other. Table 2 shows that, with the exception of compound 18, all the thiophene-3-carboxamide derivatives had effect on FluA polymerase activity, with compound 6 showing an EC$_{50}$ value of 10 μM, thus resulting slightly more effective than RBV.

Finally, for the best derivatives, 6 and 19, we investigated the antiviral effects against a number of clinical isolates of FluA other than PR8. PRA were performed using influenza strains A/Parma/24/09 (H1N1), A/Wisconsin/67/05 (H3N2), and several pandemic swine-originated influenza virus (S-OIV) clinical isolates (H1N1). As shown in Table 3, the new derivatives effectively inhibited all FluA strains tested, of both H1N1 and H3N2 subtypes, including the oseltamivir-resistant clinical isolate (A/Parma/24/09). Compound 6 was slightly more potent than 19, with EC$_{50}$ values ranging from 15 to 23 μM.

The same compounds were also assayed for their ability to inhibit the replication of FluB. When tested against Flu B/Lee/40 strain by PRA, compounds 6 and 19 were found to be effective against FluB, with EC$_{50}$ values similar to those obtained with the FluA viruses (Table 3), thus displaying broad-spectrum anti-influenza activity.
CONCLUSIONS

The viral RdRP is an attractive target to design new antivirals since it is highly conserved among Flu strains and no homologous has been found in mammalian cells. In particular, the disruption of its correct assembly through PPI inhibitors could be a promising strategy, although very few studies have been reported so far. Thanks to a SBDD approach, we recently identified a set of different small molecules able to disrupt PA-PB1 interaction and inhibit viral growth. In this study, some efforts have been pursued to evolve one of these molecules. Starting from thiophene-3-carboxamide derivative 1, more potent PA-PB1 inhibitors and anti-Flu derivatives have been achieved by mainly modifying the substituent placed at the C-2 position. Among these small molecules, compounds 6 and 19 emerged as the most potent in inhibiting the physical interaction between the two viral subunits with IC\(_{50}\) values of 32 and 35 μM, better than the hit compound and comparable to that of the reference peptide. An in-depth investigation of the binding mode of the active cycloheptathiophene-3-carboxamide derivatives, although relevant to define the mechanism of inhibition, is out of the aim of this study. However, with the purpose to rationalize the inhibition data for the most potent PA-PB1 inhibitors, their FLAP-binding modes have been compared. Based on this analysis, the presence of the bulky halogen atom in para position of compound 6 might induce a different orientation of several residues in the PA cavity, making the competition with PB1 more efficient. The good activity of 19, the only active compound that lacks the aromatic ring at the C-2 position, is more intriguing and deserves further exploration. However, modeling studies suggest that its docking pose results to be flipped with respect to that of the other compounds, with the pyridine group being located in the second hydrophobic pocket. This behavior seems to suggest that the interaction with the second pocket rather than with the central pocket should be investigated to improve activity. The last finding is supported by the promising activity displayed by compounds 17 and 18, appositely designed to increase the interaction with the second pocket, according with the optimization of the hydrophobic GRID MIFs. The PPI inhibitory activity of 6 and 19 is preserved in the cellular context, where they showed a good inhibitory effect on FluA polymerase.
activity and viral replication also encompassing a panel of clinically isolated strains, including a FluA oseltamivir-resistant, as well as FluB.

An unexpected result coming from this study is the identification of many derivatives able to inhibit the viral growth without affecting PA-PB1 interaction in vitro. For these compounds, an alternative mechanism of action should exist and will be the object of future investigations.

In conclusion, the cycloheptathiophene-3-carboxamide scaffold, when properly functionalized, emerged as particularly suitable to impart anti-Flu activity.

**EXPERIMENTAL SECTION**

**Computational methods.** The design of larger compounds to optimize the hydrophobic interaction was performed using the FLAP approach previously used to identify inhibitors of the PA-PB1 complex by virtual screening. The FLAP software is developed and licensed by Molecular Discovery Ltd. (www.moldiscovery.com). The docking procedure used by the FLAP algorithm generates the GRID Molecular Interaction Fields (MIFs) for the cavity and allows to visualize and quantify the hydrophobic and hydrophilic regions, as well as the regions where H-bond donors and acceptors might occur. Then, MIFs are also calculated for each ligand and FLAP docking poses are generated looking for the best overlap of the GRID MIFs of protein and those of the ligand.

In this study, the main cavity of the crystallographic structure of a large C-terminal fragment of PA (aa 257-716) derived from the X-ray structure named 3CM8 was explored using the GRID force field. Using the PA cavity as a template, the design of new possible inhibitors was performed using FLAP in the structure-based mode, evaluating the best pose among 50 conformers for each candidate, as previously reported. The probes used to generate the Molecular Interaction Fields were H (shape), DRY (hydrophobic interactions), N1 (H-bond donor) and O (H-bond acceptor) interactions. A second snapshot of the PA in a more relaxed form was used to dock compound 6; the method used to generate the new conformation of PA was previously reported.
FLAP binding poses reported in this study underwent a mild optimization using Sybyl 2.0. Both ligand and surrounded PA residues were energy minimized using the Powell algorithm, with a convergence gradient ≤ 0.1 kcal/mol and a maximum of 5000 cycles.

Chemistry

All reactions were routinely checked by TLC on silica gel 60F254 (Merck) and visualized by using UV or iodine. Flash column chromatography separations were carried out on Merck silica gel 60 (mesh 230-400). Melting points were determined in capillary tubes (Büchi Electrothermal Mod. 9100) and are uncorrected. Elemental analyses were performed on a Fisons elemental analyzer, Model EA1108CHN, and the data for C, H, and N are within ± 0.4% of the theoretical values. ¹H NMR and ¹³C NMR spectra were recorded at 200 MHz (Bruker Avance DPX-200) and 400 MHz (Bruker Avance DRX-400) using residual solvents such as chloroform (δ = 7.26) or dimethylsulfoxide (δ = 2.48) as an internal standard. Chemical shifts are given in ppm (δ) and the spectral data are consistent with the assigned structures. Reagents and solvents were purchased from common commercial suppliers and were used as such. After extraction, organic solutions were dried over anhydrous Na₂SO₄, filtered, and concentrated with a Büchi rotary evaporator at reduced pressure. Yields are of purified product and were not optimized. All starting materials were commercially available unless otherwise indicated. Some of the compounds reported in this study, i.e., 1, 2, 20-24, 26-30, 32, and 36 are also commercially available, but being prepared by us and not reported in any previous reference, their synthesis is described below together with the description of the new derivatives.

General procedure for the preparation of N-(2-pyridinyl)-2-aminothiophene-3-carboxamide derivatives (Method A). A mixture of 2-cyano-N-pyridin-2-ylacetamide⁴⁴ (1.0 equiv), cyclopentanone, cyclohexanone, or cycloheptanone (4.0 equiv), ammonium acetate (1.3 equiv), and glacial acetic acid (3.5 equiv) in benzene was refluxed for 16 h in a Dean-Stark apparatus. After
cooling the reaction mixture was diluted with CHCl₃ and washed with H₂O, 10% Na₂CO₃ solution, and H₂O. The organic phase was evaporated to dryness, affording the crude Knoevenagel product, which was used in the next step without further purification. This material was dissolved in EtOH, added of sulphur (4.0 equiv) and N,N-diethylamine (4.0 equiv), and maintained at 40-50 °C for 1.5 h. After cooling, the reaction mixture was evaporated to dryness and purified by flash chromatography, eluting with EtOAc/cyclohexane (15%), and crystallized by EtOH.

2-Amino-N-(2-pyridinyl)-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (19). The title compound was prepared starting from cycloheptanone by Method A, in 59% yield: mp 176-178 °C (dec); ¹H-NMR (CDCl₃) δ 1.70-1.90 (m, 6H, cycloheptane CH₂), 2.60-2.70 and 2.80-2.90 (m, each 2H, cycloheptane CH₂), 4.80 (bs, 2H, NH₂), 7.00 (dd, J = 1.1 and 7.0 Hz, 1H, pyridine CH), 7.70 (dt, J = 1.4 and 7.0 Hz, 1H, pyridine CH), 8.10 (bs, 1H, NH), 8.25-8.30 (m, 2H, pyridine CH); ¹³C-NMR (CDCl₃) δ 27.2, 27.5, 28.6, 29.2, 31.5, 113.6, 114.3, 119.2, 124.0, 135.0, 138.8, 146.9, 151.5, 155.8, 164.4. Anal. (C₁₅H₁₇N₃O₅S) C, H, N.

2-Amino-N-(2-pyridinyl)-4,5,6,7-tetrahydro-1-benzothiophene-3-carboxamide (37). The title compound was prepared starting from cyclohexanone by Method A, in 41% yield: mp 158-159 °C; ¹H-NMR (CDCl₃) δ 1.80-1.90 (m, 4H, cyclohexane CH₂), 2.50-2.60 and 2.80-2.90 (m, each 2H, cyclohexane CH₂), 6.20 (bs, 2H, NH₂), 7.00 (dd, J = 5.0 and 7.0 Hz, 1H, pyridine CH), 7.70 (dt, J = 1.4 and 7.0 Hz, 1H, pyridine CH), 8.10 (bs, 1H, NH), 8.25-8.30 (m, 2H, pyridine CH); ¹³C-NMR (CDCl₃) δ 22.8, 22.9, 24.5, 27.2, 108.5, 114.0, 119.1, 119.2, 128.5, 138.1, 147.8, 151.9, 160.8, 164.4.

2-Amino-N-(2-pyridinyl)-5,6-dihydro-4H-cyclopenta[b]thiophene-3-carboxamide (38). The title compound was prepared starting from cyclopentanone by Method A, in 46% yield: mp 159-160 °C; ¹H-NMR (CDCl₃) δ 2.45 (q, J = 7.1 Hz, 2H, cyclopentane CH₂), 2.80 and 3.10 (t, J = 7.1 Hz, each 2H, cyclopentane CH₂), 6.25 (bs, 2H, NH₂), 7.00 (dd, J = 5.0 and 7.0 Hz, 1H, pyridine CH), 7.70 (dt, J = 1.4 and 7.0 Hz, 1H, pyridine CH), 8.10 (bs, 1H, NH), 8.25-8.30 (m, 2H, pyridine CH);
C-NMR (CDCl$_3$) $\delta$ 27.4, 28.6, 30.7, 104.6, 113.7, 119.1, 122.5, 138.1, 138.2, 147.9, 151.8, 164.0, 166.5.

**General procedure for C-2 amidation (Method B).** A solution of the appropriate 2-aminothiophene derivative (1.0 equiv) in pyridine was added of the suitable acyl chloride (2.0 equiv). The reaction mixture was maintained at room temperature for 1 h, and worked up and purified as defined in the description of the compounds.

2-[(2-Fluorobenzoyl)amino]-N-(2-pyridinyl)-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (1). The title compound was prepared starting from 19 by Method B, using 2-fluorobenzoyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and purified by flash chromatography eluting with EtOAc/cyclohexane (15%) and then crystallized by EtOH, to give 1 in 42% yield: mp 206-209 °C; $^1$H-NMR $\delta$ 1.70-1.90 (m, 6H, cycloheptane CH$_2$), 2.70-2.75 and 2.95-3.00 (m, each 2H, cycloheptane CH$_2$), 7.05 (ddd, $J = 0.9, 5.0$ and $7.0$ Hz, 1H, pyridine CH), 7.20 (dd, $J = 8.3$ and $12.0$ Hz, 1H, aromatic CH), 7.30 (dt, $J = 0.9$ and $7.6$ Hz, 1H, aromatic CH), 7.50 (dq, $J = 1.4$ and $7.3$ Hz, 1H, aromatic CH), 7.70 (dt, $J = 1.4$ and $7.0$ Hz, 1H, pyridine CH), 8.10-8.20 (m, 2H, aromatic CH and NH), 8.20 (d, $J = 4.4$ Hz, 1H, pyridine CH), 8.30 (d, $J = 8.4$ Hz, pyridine CH), 13.00 (d, $J = 11.0$ Hz, 1H, NH); $^{13}$C-NMR (CDCl$_3$) $\delta$ 27.3, 27.6, 28.6, 29.0, 31.7, 114.3, 116.3 (d, $J_{C,F} = 23$ Hz), 118.8, 119.8, 119.9, 124.9, 132.1, 133.0, 133.2, 134.1 (d, $J_{C,F} = 9$ Hz), 138.4, 141.4, 147.9, 151.2, 159.8, 160.6 (d, $J_{C,F} = 248$ Hz), 164.6. Anal. (C$_{22}$H$_{20}$FN$_3$O$_2$S) C, H, N.

The physical-chemical properties are comparable to those of the commercial compound (STK063428) purchased from Vitas-M (Moscow, Russia) including the purity that is 100% for both the compounds, as assessed by UV chromatogram at 280 nm.

2-(Benzoylamino)-N-pyridin-2-yl-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (2). The title compound was prepared starting from 19 by Method B, using benzooyl chloride. The reaction mixture was poured into ice/water obtained a precipitate which was filtered and purified by flash chromatography eluting with EtOAc/petroleum ether (15%) and then washed
with cyclohexane, to give 2 in 34% yield: mp 208-210 °C; $^1$H-NMR (DMSO $d_6$) $\delta$ 1.45-1.70 (m, 6H, cycloheptane CH$_2$), 1.70-1.85 and 2.65-2.80 (m, each 2H, cycloheptane CH$_2$), 7.05-7.10 (m, 1H, pyridine CH), 7.40-7.60 (m, 3H, aromatic CH), 7.65-7.85 (m, 3H, aromatic CH and pyridine CH), 8.15 (d, $J = 8.2$ Hz, 1H, pyridine CH), 8.30 (d, $J = 4.0$ Hz, 1H, pyridine CH), 10.40 and 11.00 (s, each 1H, NH). Anal. (C$_{22}$H$_{21}$N$_3$O$_2$S) C, H, N.

2-[(3-Fluorobenzoyl)amino]-N-(2-pyridinyl)-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (3). The title compound was prepared starting from 19 by Method B, using 3-fluorobenzoyl chloride. The reaction mixture was poured into ice/water and extracted with EtOAc. The organic layer was evaporated to dryness, obtaining a solid which was purified by flash chromatography eluting with EtOAc/cyclohexane (15%) and then crystallized by EtOH, to give 3 in 39% yield: mp 215-216 °C; $^1$H-NMR (CDCl$_3$) $\delta$ 1.75-1.80 (m, 6H, cycloheptane CH$_2$), 1.85-1.90, 2.80-2.85 and 3.00-3.05 (m, each 2H, cycloheptane CH$_2$), 7.10 (ddd, $J = 0.9$, 5.0 and 7.0 Hz, 1H, pyridine CH), 7.30 (dt, $J = 2.5$ and 8.9 Hz, 1H, aromatic CH), 7.50 (dq, $J = 2.5$ and 5.5 Hz, 1H, aromatic CH), 7.70-7.80 (m, 3H, pyridine CH and aromatic CH), 8.25 (d, $J = 4.4$ Hz, 1H, pyridine CH), 8.30 (bs, 1H, NH), 8.35 (d, $J = 8.3$ Hz, 1H, pyridine CH), 12.00 (s, 1H, NH); $^{13}$C-NMR (CDCl$_3$) $\delta$ 27.2, 27.5, 28.6, 29.1, 31.5, 114.3, 114.8 (d, $J_{C,F} = 28$ Hz), 117.9, 119.3 (d, $J_{C,F} = 21$ Hz), 120.0, 122.7 (d, $J_{C,F} = 3$ Hz), 130.5 (d, $J_{C,F} = 8$ Hz), 132.8, 132.9, 134.9 (d, $J_{C,F} = 7$ Hz), 138.3, 142.8, 148.1, 151.0, 162.1, 162.9 (d, $J_{C,F} = 248$ Hz), 164.9. Anal. (C$_{22}$H$_{20}$FN$_3$O$_2$S) C, H, N.

2-[(4-Fluorobenzoyl)amino]-N-(2-pyridinyl)-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (4). The title compound was prepared starting from 19 by Method B, using 4-fluorobenzoyl chloride. The reaction mixture was poured into ice/water and extracted with EtOAc. The organic layer was evaporated to dryness, obtaining a solid which was purified by flash chromatography eluting with EtOAc/cyclohexane (15%), to give 4 in 44% yield: mp 192-193 °C; $^1$H-NMR (CDCl$_3$) $\delta$ 1.70-1.80 (m, 4H, cycloheptane CH$_2$), 1.85-1.90, 2.75-2.80 and 3.00-3.05 (m, each 2H, cycloheptane CH$_2$), 7.10 (ddd, $J = 0.9$ and 5.0 and 7.0 Hz, 1H, pyridine CH), 7.15-7.20 (m, 2H, aromatic CH), 7.75 (dt, $J = 1.4$ and 7.0 Hz, 1H, pyridine CH), 7.95-8.05 (m, 2H, aromatic...
CH), 8.15-8.20 (m, 2H, pyridine CH and NH), 8.30 (d, $J = 8.3$ Hz, 1H, pyridine CH), 12.00 (s, 1H, NH); $^{13}$C-NMR (CDCl$_3$) $\delta$ 27.2, 27.5, 28.5, 29.1, 31.5, 114.3, 115.9 (d, $J_{C,F} = 22$ Hz), 117.6, 120.0, 128.8, 129.9 (d, $J_{C,F} = 9$ Hz), 132.6, 132.8, 138.3, 143.2, 148.1, 151.0, 162.3, 163.9, 165.2 (d, $J_{C,F} = 252$ Hz), 166.5. Anal. (C$_{22}$H$_{20}$FN$_3$O$_2$S) C, H, N.

2-[(2-Chlorobenzoyl)amino]-N-(2-pyridinyl)-5,6,7,8-tetrahydro-4H-cyclohept[b]thiophene-3-carboxamide (5). The title compound was prepared starting from 19 by Method B, using 2-chlorobenzoyl chloride. The reaction mixture was poured into ice/water and extracted with EtOAc. The organic layer was evaporated to dryness, obtaining a solid which was purified by flash chromatography eluting with EtOAc/cyclohexane (15%) and then crystallized by EtOH, to give 5 in 31% yield: mp 160-161 °C; $^1$H-NMR (CDCl$_3$) $\delta$ 1.65-1.75 (m, 4H, cycloheptane CH$_2$), 1.85-1.90, 2.75-2.80 and 2.90-2.95 (m, each 2H, cycloheptane CH$_2$), 7.05 (ddd, $J = 0.9$ and 5.0 and 7.0 Hz, 1H, pyridine CH), 7.30-7.45 (m, 3H, aromatic CH), 7.70 (dt, $J = 1.4$ and 7.0 Hz, 1H, pyridine CH), 7.75 (dd, $J = 1.6$ and 7.5 Hz, 1H, aromatic CH), 8.15 (d, $J = 4.4$ Hz, 1H, pyridine CH), 8.25 (d, $J = 8.3$ Hz, 1H, pyridine CH), 8.40 (bs, 1H, NH), 11.40 (s, 1H, NH); $^{13}$C-NMR (CDCl$_3$) $\delta$ 27.3, 27.5, 28.6, 29.0, 31.7, 114.2, 118.8, 120.0, 127.1, 130.6, 130.7, 131.4, 132.0, 133.0, 133.1, 133.3, 138.3, 141.4, 148.0, 151.1, 162.8, 164.6. Anal. (C$_{22}$H$_{20}$FN$_3$O$_2$S) C, H, N.

2-(4-Chlorobenzamido)-N-(pyridin-2-yl)-5,6,7,8-tetrahydro-4H-cyclohept[b]thiophene-3-carboxamide (6). The title compound was prepared starting from 19 by Method B, using 4-chlorobenzoyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and purified by flash chromatography eluting with EtOAc/cyclohexane (20%), to give 6 in 29% yield: mp 222-223 °C; $^1$H-NMR (CDCl$_3$) $\delta$ 1.70-1.80 (m, 4H, cycloheptane CH$_2$), 1.85-1.90, 2.75-2.80 and 3.00-3.05 (m, each 2H, cycloheptane CH$_2$), 7.10 (ddd, $J = 0.9$ and 5.0 and 7.0 Hz, 1H, pyridine CH), 7.45 (d, $J = 8.4$ Hz, 2H, aromatic CH), 7.75 (dt, $J = 1.4$ and 7.0 Hz, 1H, pyridine CH), 7.90 (d, $J = 8.4$ Hz, 2H, aromatic CH), 8.10 (bs, 1H, NH), 8.25-8.30 (m, 2H, pyridine CH), 12.00 (s, 1H, NH). Anal. (C$_{22}$H$_{20}$ClN$_3$O$_2$S) C, H, N.
2-[(2-Chloro-4-fluorobenzoyl)amino]-N-pyridin-2-yl-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (7). The title compound was prepared starting from 19 by Method B, using 2-chloro-4-fluorobenzoyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and purified by flash chromatography eluting with EtOAc/cyclohexane (15%), to give 7 in 25% yield: mp 162-163 °C; \(^1\)H-NMR (CDCl\(_3\)) \(\delta\) 1.70-1.80 (m, 4H, cycloheptane CH\(_2\)), 1.85-1.90, 2.75-2.80 and 3.00-3.05 (m, each 2H, cycloheptane CH\(_2\)), 7.05-7.15 (m, 2H, aromatic CH and pyridine CH), 7.20 (dd, \(J = 2.4\) and 8.4 Hz, 1H, aromatic CH), 7.70 (dt, \(J = 1.4\) and 7.0 Hz, 1H, pyridine CH), 7.80 (dd, \(J = 6.0\) and 8.4 Hz, 1H, aromatic CH), 8.00 (bs, 1H, NH), 8.20 (d, \(J = 8.4\) Hz, 1H, pyridine CH), 8.30 (d, \(J = 4.6\) Hz, 1H, pyridine CH), 11.50 (s, 1H, NH). Anal. (C\(_{22}\)H\(_{19}\)ClFN\(_3\)O\(_2\)S) C, H, N.

2-[(2,4-Dichlorobenzoyl)amino]-N-pyridin-2-yl-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (8). The title compound was prepared starting from 19 by Method B, using 2,4-dichlorobenzoyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and crystallized by EtOH, to give 8 in 30% yield: mp 190-191 °C; \(^1\)H-NMR (CDCl\(_3\)) \(\delta\) 1.70-1.80 (m, 4H, cycloheptane CH\(_2\)), 1.85-1.90, 2.75-2.80 and 3.00-3.05 (m, each 2H, cycloheptane CH\(_2\)), 7.05 (ddd, \(J = 0.9\) and 5.0 and 7.0 Hz, 1H, pyridine CH), 7.35 (dd, \(J = 1.8\) and 8.4 Hz, 1H, aromatic CH), 7.45 (d, \(J = 1.8\) Hz, 1H, aromatic CH), 7.65-7.75 (m, 2H, aromatic CH and pyridine CH), 8.10 (bs, 1H, NH), 8.20-8.25 (m, 2H, pyridine CH), 11.50 (s, 1H, NH). Anal. (C\(_{22}\)H\(_{19}\)Cl\(_2\)N\(_3\)O\(_2\)S) C, H, N.

2-[(Cyclohexylcarbonyl)amino]-N-pyridin-2-yl-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (9). The title compound was prepared starting from 19 by Method B, using cyclohexanecarbonyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and purified by flash chromatography eluting with EtOAc/petroleum ether (15%) to give 9 in 20% yield: mp 201-204 °C; \(^1\)H-NMR (DMSO \(d_6\)) \(\delta\) 1.00-1.80 (m, 17H, cyclohexane CH\(_2\), cyclohexane CH, and cycloheptane CH\(_2\)), 2.50-2.65 (m, 4H, cycloheptane CH\(_2\)), 7.05 (dd, \(J = 5.0\) and 7.3 Hz, 1H, pyridine CH), 7.75 (dt, \(J = 2.0\) and 9.2 Hz, 1H, pyridine CH), 8.10
(d, J = 8.1 Hz, 1H, pyridine CH), 8.25 (d, J = 3.6 Hz, 1H, pyridine CH), 10.20 and 10.30 (s, each 1H, NH). Anal. (C_{22}H_{27}N_{3}O_{2}S) C, H, N.

2-[[4-Fluorophenyl]acetyl]amino]-N-pyridin-2-yl-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (10). The title compound was prepared starting from 19 by Method B, using (4-fluorophenyl)acetyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and purified by flash chromatography eluting with EtOAc/cyclohexane (15%), to give 10 in 25% yield: mp 159-160 °C; 1H-NMR (CDCl_3) δ 1.60-1.70 (m, 4H, cycloheptane CH_2), 1.80-1.85, 2.70-2.75 and 2.90-2.95 (m, each 2H, cycloheptane CH_2), 3.75 (s, 2H, CH_2), 7.00-7.10 (m, 3H, aromatic CH and pyridine CH), 7.30-7.35 (m, 2H, aromatic CH), 7.70 (dt, J = 1.4 and 7.0 Hz, 1H, pyridine CH), 7.90 (bs, 1H, NH), 8.15 (d, J = 8.3 Hz, 1H, pyridine CH), 8.25 (d, J = 4.6 Hz, 1H, pyridine CH), 10.75 (s, 1H, NH). Anal. (C_{23}H_{22}FN_{3}O_{2}S) C, H, N.

2-[[4-Chlorophenyl]acetyl]amino]-N-pyridin-2-yl-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (11). The title compound was prepared starting from 19 by Method B, using (4-chlorophenyl)acetyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and purified by flash chromatography eluting with EtOAc/cyclohexane (15%), to give 11 in 27% yield: mp 169-170 °C; 1H-NMR (CDCl_3) δ 1.60-1.70 (m, 4H, cycloheptane CH_2), 1.80-1.85, 2.70-2.75 and 2.90-2.95 (m, each 2H, cycloheptane CH_2), 3.75 (s, 2H, CH_2), 7.05 (ddd, J = 0.9, 5.0 and 7.0 Hz, 1H, pyridine CH), 7.25 and 7.30 (d, J = 8.3 Hz, each 2H, aromatic CH), 7.75 (dt, J = 1.4 and 7.0 Hz, 1H, pyridine CH), 7.85 (bs, 1H, NH), 8.15 (d, J = 8.3 Hz, 1H, pyridine CH), 8.25 (d, J = 4.6 Hz, 1H, pyridine CH), 10.75 (s, 1H, NH). Anal. (C_{23}H_{22}ClN_{3}O_{2}S) C, H, N.

2-[(Phenylacetyl]amino]-N-pyridin-2-yl-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (12). The title compound was prepared starting from 19 by Method B, using phenylacetyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and purified by flash chromatography eluting with EtOAc/cyclohexane (15%), and then
crystallized by EtOH, to give 12 in 20% yield: mp 165-167 °C; 1H-NMR (CDCl₃) δ 1.60-1.70 (m, 4H, cycloheptane CH₂), 1.80-1.85, 2.70-2.75 and 2.90-2.95 (m, each 2H, cycloheptane CH₂), 3.75 (s, 2H, CH₂), 7.10 (ddd, J = 0.9, 5.0 and 7.0 Hz, 1H, pyridine CH), 7.25-7.40 (m, 5H, aromatic CH), 7.75 (dt, J = 1.4 and 7.0 Hz, 1H, pyridine CH), 8.15-8.20 (m, 2H, pyridine CH), 8.40 (bs, 1H, NH), 10.75 (s, 1H, NH). Anal. (C₂₃H₂₃N₃O₂S) C, H, N.

2-[(3-(4-Fluorophenyl)propanoyl)amino]-N-pyridin-2-yl-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (13). The title compound was prepared starting from 19 by Method B, using 3-(4-fluorophenyl)propanoyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and crystallized twice by EtOH, to give 13 in 24% yield: mp 132-133 °C; 1H-NMR (CDCl₃) δ 1.60-1.70 (m, 4H, cycloheptane CH₂), 1.80-1.85 (m, 2H, cycloheptane CH₂), 2.70-2.75 and 2.90-3.00 (m, each 4H, cycloheptane CH₂ and CH₂CH₂), 6.85-6.95 (m, 2H, aromatic CH and pyridine CH), 7.10-7.20 (m, 3H, aromatic CH), 7.80 (dt, J = 1.4 and 7.0 Hz, 1H, pyridine CH), 8.20 (d, J = 8.3 Hz, 1H, pyridine CH), 8.30 (d, J = 4.6 Hz, 1H, pyridine CH), 8.75 (bs, 1H, NH), 10.70 (s, 1H, NH). Anal. (C₂₄H₂₄FN₃O₂S) C, H, N.

2-[(Cyclohexylacetyl)amino]-N-pyridin-2-yl-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (14). The title compound was prepared starting from 19 by Method B, using cyclohexylacetyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and crystallized twice by EtOH, to give 14 in 38% yield: mp 181-182 °C (dec); 1H-NMR (CDCl₃) δ 0.95-1.30 (m, 5H, cyclohexane CH₂), 1.60-1.75 (m, 10H, cycloheptane CH₂ and cyclohexane CH₂), 1.80-1.85 (m, 2H, cycloheptane CH₂), 2.25 (d, J = 7.0 Hz, 2H, CH₂), 2.70-2.75 and 2.95-3.00 (m, each 2H, cycloheptane CH₂), 7.10-7.20, 7.75-7.80, and 8.20-8.25 (m, each 1H, pyridine CH), 8.30 (d, J = 4.6 Hz, 1H, pyridine CH), 8.45 (bs, 1H, NH), 10.75 (s, 1H, NH). Anal. (C₂₃H₂₉N₃O₂S) C, H, N.

2-[(3-(4-Chlorophenyl)propanoyl)amino]-N-pyridin-2-yl-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (15). The title compound was prepared starting from 19 by Method B, using 3-(4-chlorophenyl)propanoyl chloride. The reaction mixture was poured into
ice/water obtaining a precipitate which was filtered and purified by flash chromatography eluting with EtOAc/cyclohexane (15%), and then crystallized by EtOH, to give 15 in 42% yield: mp 125-126 °C; ¹H-NMR (CDCl₃) δ 1.60-1.70 (m, 4H, cycloheptane CH₂), 1.80-1.85 (m, 2H, cycloheptane CH₂), 2.70-2.75 (m, 4H, cycloheptane CH₂ and CH₃CH₂), 2.80-2.85 (m, 2H, cycloheptane CH₂), 3.00 (t, J = 7.5 Hz, 2H, CH₂CH₂), 7.10 (ddd, J = 0.9, 5.0 and 7.0 Hz, 1H, pyridine CH), 7.05-7.10 and 7.15-7.20 (m, each 2H, aromatic CH), 7.75 (dt, J = 1.4 and 7.0 Hz, 1H, pyridine CH), 8.20 (d, J = 8.3 Hz, 1H, pyridine CH), 8.25 (d, J = 4.6 Hz, 1H, pyridine CH), 8.40 (bs, 1H, NH), 10.75 (s, 1H, NH). Anal. (C₂₄H₂₄ClN₃O₂S) C, H, N.

2-[(3-Phenylpropanoyl)amino]-N-pyridin-2-yl-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (16). The title compound was prepared starting from 19 by Method B, using 3-phenylpropanoyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and purified by flash chromatography eluting with EtOAc/cyclohexane (15%), and then crystallized by EtOH, to give 16 in 28% yield: mp 135-136 °C; ¹H-NMR (CDCl₃) δ 1.60-1.70 (m, 4H, cycloheptane CH₂), 1.80-1.85 (m, 2H, cycloheptane CH₂), 2.70-2.75 (m, 4H, cycloheptane CH₂ and CH₃CH₂), 2.80-2.85 (m, 2H, cycloheptane CH₂), 3.00 (t, J = 7.5 Hz, 2H, CH₂CH₂), 7.10-7.25 (m, 6H, aromatic CH and pyridine CH), 7.85 (dt, J = 1.4 and 7.0 Hz, 1H, pyridine CH), 8.20 (d, J = 8.3 Hz, 1H, pyridine CH), 8.30 (d, J = 4.6 Hz, 1H, pyridine CH), 8.75 (bs, 1H, NH), 10.70 (s, 1H, NH). Anal. (C₂₄H₂₅N₃O₂S) C, H, N.

N-Pyridin-2-yl-2-[(quinolin-6-ylacetyl)amino]-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (17). To a solution of 19 (0.5 g, 1.75 mmol) in THF (40 mL) was added quinolin-6-ylacetic acid (0.3 g, 1.59 mmol) and DMTMM. After 24 h, the reaction mixture was poured into ice/water, obtaining a precipitate which was filtered and crystallized by cyclohexane/EtOAc, to give 17 (0.4 g, 55%): mp 122-123 °C; ¹H-NMR (CDCl₃) δ 1.50-1.55 (m, 4H, cycloheptane CH₂), 1.55-2.00, 2.40-2.60, and 2.80-3.00 (m, each 2H, cycloheptane CH₂), 3.90 (s, 2H, CH₃), 7.00-7.10 (m, 1H, pyridine CH), 7.25 (s, 1H, quinoline CH), 7.40-7.50 (m, 1H, quinoline CH), 7.60-7.75 (m, 2H, quinoline CH and pyridine CH), 7.85 (s, 1H, quinoline CH), 7.95 (d, J = 8.0 Hz, 1H, quinoline CH).
8.10-8.30 (m, 3H, quinoline CH and pyridine CH), 9.00 and 11.00 (s, each 1H, NH). Anal. (C_{36}H_{24}N_{4}O_{2}S) C, H, N.

2-\{[(3-Methoxy-1-benzothien-2-yl)acetyl]amino\}-N-pyridin-2-yl-5,6,7,8-tetrahydro-4H-cyclohepta[\beta]thiophene-3-carboxamide (18). The title compound was prepared by using the same procedure used for the synthesis of 17 replacing quinolin-6-ylacetic acid with (3-methoxy-1-benzothien-2-yl)acetic acid, in 16% yield after purification by flash chromatography eluting with EtOAc/cyclohexane (20%): mp 153-155 °C; \textsuperscript{1}H-NMR (DMSO \textit{d}_6) \textsuperscript{\delta} 1.50-1.70 (m, 4H, cycloheptane CH\textsubscript{2}), 1.75-1.80 (m, 2H, cycloheptane CH\textsubscript{2}), 2.60-2.70 (m, 4H, cycloheptane CH\textsubscript{2}), 3.85 (s, 3H, OCH\textsubscript{3}), 4.00 (s, 2H, CH\textsubscript{2}), 7.05-7.15 (m, 1H, pyridine CH), 7.30-7.40 (m, 2H, benzothiene CH), 7.65-7.70 (m, 1H, pyridine CH), 7.75-7.90 (m, 2H, benzothiene CH), 1.15 (d, \textit{J} = 8.36 Hz, 1H, pyridine CH), 8.25-8.30 (m, 1H, pyridine CH), 10.45 and 10.70 (s, each 1H, NH). Anal. (C_{26}H_{24}N_{4}O_{2}S) C, H, N.

2-\{(2-Fluorobenzoyl)amino\}-N-(2-pyridinyl)-4,5,6,7-tetrahydro-1-benzothiophene-3-carboxamide (31). The title compound was prepared starting from 37 by Method B, using 2-fluorobenzoyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and purified by flash chromatography eluting with EtOAc/cyclohexane (15%), to give 31 in 35% yield: 204-205 °C; \textsuperscript{1}H-NMR (CDCl\textsubscript{3}) \textsuperscript{\delta} 1.80-1.90 (m, 4H, cyclohexane CH\textsubscript{2}), 2.70-2.75 and 2.85-2.90 (m, each 2H, cyclohexane CH\textsubscript{2}), 7.05 (dd, \textit{J} = 5.0 and 7.0 Hz, 1H, pyridine CH), 7.20 (dd, \textit{J} = 8.3 and 12.0 Hz, 1H, aromatic CH), 7.30 (t, \textit{J} = 7.6 Hz, 1H, aromatic CH), 7.50 (dq, \textit{J} = 1.4 and 7.3 Hz, 1H, aromatic CH), 7.70 (dt, \textit{J} = 1.4 and 7.0 Hz, 1H, pyridine CH), 8.20 (dt, \textit{J} = 1.4 and 7.7 Hz, 1H, aromatic CH), 8.25 (d, \textit{J} = 4.4 Hz, 1H, pyridine CH), 8.30-8.35 (m, 2H, pyridine CH and NH), 13.00 (d, \textit{J} = 11.0 Hz, 1H, NH); \textsuperscript{13}C-NMR (CDCl\textsubscript{3}) \textsuperscript{\delta} 22.5, 22.9, 24.3, 26.7, 114.5, 115.1, 116.4 (d, \textit{J}_{CF} = 23 Hz), 119.8, 120.1 (d, \textit{J}_{CF} = 11 Hz), 124.8 (d, \textit{J}_{CF} = 3 Hz), 127.0, 128.8, 132.1, 134.1 (d, \textit{J}_{CF} = 9 Hz), 138.3, 146.3, 147.9, 151.2, 160.0, 160.7 (d, \textit{J}_{CF} = 249 Hz) 164.2. Anal. (C_{21}H_{18}F_{2}N_{3}O_{2}S) C, H, N.
2-[(2-Fluorobenzoyl)amino]-N-(2-pyridinyl)-5,6-dihydro-4H-cyclopenta[b]thiophene-3-carboxamide (32). The title compound was prepared starting from 38 by Method B, using 2-fluorobenzoyl chloride. The reaction mixture was poured into ice/water and extracted with EtOAc. The organic layer was evaporated to dryness, obtaining a solid which was purified by flash chromatography eluting with EtOAc/cyclohexane (15%) and then crystallized by EtOH, to give 32 in 37% yield: mp 184-185 °C; \(^1\)H-NMR (CDCl\(_3\)) \(\delta 2.55 (q, J = 7.1 \text{ Hz}, 2\text{H, cyclopentane CH}_2), 2.80\) and 3.20 (t, \(J = 7.1 \text{ Hz}, \text{each } 2\text{H, cyclopentane CH}_2), 7.00 (dd, \(J = 5.0 \text{ and } 7.0 \text{ Hz, 1H, pyridine CH}), 7.20 (dd, \(J = 8.3 \text{ and } 12.0 \text{ Hz, 1H, aromatic CH}), 7.30 (t, \(J = 7.6 \text{ Hz, 1H, aromatic CH}), 7.55 (dq, \(J = 1.4 \text{ and } 7.3 \text{ Hz, 1H, aromatic CH}), 7.70 (dt, \(J = 1.4 \text{ and } 7.0 \text{ Hz, 1H, pyridine CH}), 8.20 (dt, \(J = 1.4 \text{ and } 7.7 \text{ Hz, 1H, aromatic CH}), 8.25 (d, \(J = 4.4 \text{ Hz, 1H, pyridine CH}), 8.30-8.35 (m, 2\text{H, pyridine CH and NH}), 13.00 (d, \(J = 11.0 \text{ Hz, 1H, NH}); \(^{13}\)C-NMR (CDCl\(_3\)) \(\delta 28.2, 28.6, 30.3, 111.2, 114.2, 116.4 (d, \(J_{CF} = 23 \text{ Hz}), 119.8, 120.0, 124.8 (d, \(J_{CF} = 3 \text{ Hz}), 132.1, 134.2 (d, \(J_{CF} = 9 \text{ Hz}), 134.4, 137.1, 138.2, 148.0, 150.9, 151.2, 159.9, 160.7 (d, \(J_{CF} = 249 \text{ Hz}), 163.6. \text{Anal. (C}_{20}\text{H}_{16}\text{FN}_{3}\text{O}_{2}\text{S) C, H, N.}

2-[(2-Fluorobenzoyl)amino]-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide (20). The title compound was prepared starting from 2-amino-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxamide 39 by Method B, using 2-fluorobenzoyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and crystallized by EtOH, to give 20 in 40% yield: mp 233-234 °C; \(^1\)H-NMR (CDCl\(_3\)) \(\delta 1.60-1.70 (m, 4\text{H, cycloheptane CH}_2), 1.85-1.90, 2.75-2.80 \text{ and } 2.85-2.90 (m, \text{each } 2\text{H, cycloheptane CH}_2), 5.75 (bs, 2\text{H, NH}_2), 7.20 (dd, \(J = 8.3 \text{ and } 12.0 \text{ Hz, 1H, aromatic CH}), 7.30 (dt, \(J = 0.9 \text{ and } 7.6 \text{ Hz, 1H, aromatic CH}), 7.50 (dq, \(J = 1.4 \text{ and } 7.3 \text{ Hz, 1H, aromatic CH}), 8.25 (dt, \(J = 1.7 \text{ and } 7.8 \text{ Hz, 1H, aromatic CH}), 12.25 (d, \(J = 11.0 \text{ Hz, 1H, NH}); \(^{13}\)C-NMR (CDCl\(_3\)) \(\delta 27.1, 27.6, 28.5, 28.8, 31.7, 116.3 (d, \(J_{CF} = 23 \text{ Hz}), 117.5, 121.8, 124.8 (d, \(J_{CF} = 3 \text{ Hz}), 132.1, 132.6, 133.4, 134.0 (d, \(J_{CF} = 9 \text{ Hz}), 141.8, 159.8, 160.7 (d, \(J_{CF} = 249 \text{ Hz}), 168.2. \text{Anal. (C}_{17}\text{H}_{18}\text{FN}_{2}\text{O}_{2}\text{S) C, H, N.}
Ethyl 2-[(2-fluorobenzoyl)amino]-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxylate (21). The title compound was prepared starting from ethyl 2-amino-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxylate 42 by Method B, using 2-fluorobenzoyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and crystallized by EtOH, to give 21 in 100% yield: mp 117-118 °C; ¹H-NMR (CDCl₃) δ 1.30 (t, J = 7.1 Hz, 3H, CH₂CH₃), 1.60-1.70 (m, 4H, cycloheptane CH₂), 1.80-1.85, 2.70-2.75 and 3.05-3.10 (m, each 2H, cycloheptane CH₂), 4.35 (q, J = 7.1 Hz, 2H, CH₂CH₃), 7.20 (dd, J = 8.3 and 12.0 Hz, 1H, aromatic CH), 7.35 (dt, J = 1.4 and 7.3 Hz, 1H, aromatic CH), 12.25 (d, J = 11.0 Hz, 1H, NH); ¹³C-NMR (CDCl₃) δ 14.3, 26.9, 27.8, 28.2, 28.6, 32.2, 60.7, 114.0, 116.3 (d, Jₐ-C = 24 Hz), 119.9 (d, Jₐ-C = 3 Hz), 131.7, 132.2 (d, Jₐ-C = 1 Hz), 134.1 (d, Jₐ-C = 9 Hz), 137.0, 144.5, 159.7 (d, Jₐ-C = 3 Hz), 160.6 (d, Jₐ-C = 248 Hz), 166.1. Anal. (C₁₉H₂₁FNO₃S) C, H, N.

Ethyl 2-[(4-fluorobenzoyl)amino]-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxylate (23). The title compound was prepared starting from 42 by Method B, using 4-fluorobenzoyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and crystallized by EtOH, to give 23 in 64% yield: mp 117-118 °C; ¹H-NMR (CDCl₃) δ 1.35 (t, J = 7.1 Hz, 2H, CH₂CH₃), 1.60-1.70 (m, 4H, cycloheptane CH₂), 1.80-1.85, 2.70-2.75 and 3.05-3.10 (m, each 2H, cycloheptane CH₂), 4.35 (q, J = 7.1 Hz, 3H, CH₂CH₃), 7.10-7.20 and 7.95-8.05 (m, each 2H, aromatic CH), 12.25 (s, 1H, NH). Anal. (C₁₉H₂₂FNO₃S) C, H, N.

Ethyl 2-[(2-chlorobenzoyl)amino]-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxylate (24). The title compound was prepared starting from 42 by Method B, using 2-chlorobenzoyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and crystallized by EtOH, to give 24 in 46% yield: mp 91-92 °C; ¹H-NMR (CDCl₃) δ 1.35 (t, J = 7.1 Hz, 2H, CH₂CH₃), 1.60-1.70 (m, 4H, cycloheptane CH₂), 1.80-1.85, 2.70-2.75 and 3.05-3.10 (m, each 2H, cycloheptane CH₂), 4.30 (q, J = 7.1 Hz, 3H, CH₂CH₃), 7.30-7.45
(m, 3H, aromatic CH), 7.75 (dd, J = 1.5 and 7.5 Hz, 1H, aromatic CH), 11.80 (s, 1H, NH). Anal. (C_{19}H_{20}ClNO_{3}S) C, H, N.

**Ethyl 2-[(4-methoxybenzoyl)amino]-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxylate (26).** The title compound was prepared starting from 42 \(^{47}\) by Method B, using 4-methoxybenzoyl chloride. The reaction mixture was poured into ice/water obtaining a precipitate which was filtered and crystallized by EtOH, to give 26 in 45% yield: mp 127-128 °C; \(^1\)H-NMR (CDCl\(_3\)) \(\delta\) 1.45 (t, \(J = 7.1\) Hz, 3H, CH\(_2\)CH\(_3\)), 1.60-1.70 (m, 4H, cycloheptane CH\(_2\)), 1.80-1.85, 2.70-2.75 and 3.05-3.10 (m, each 2H, cycloheptane CH\(_2\)), 3.85 (s, 3H, CH\(_3\)), 4.35 (q, \(J = 7.1\) Hz, 2H, CH\(_2\)CH\(_3\)), 6.95-7.00 and 7.90-7.95 (m, each 2H, aromatic CH), 12.10 (s, 1H, NH). Anal. (C_{20}H_{23}NO_{4}S) C, H, N.

**General procedure for hydrolysis (Method C).** A suspension of the appropriate ethyl thiophene-3-carboxylate (1.0 equiv) and LiOH (4.0 equiv) in a mixture H\(_2\)O/THF (1:1) was maintained at 50 °C for 48 h. After cooling the reaction mixture was acidified (pH 6) with 2N HCl and the precipitate was filtered, washed with water and crystallized by EtOH.

**2-[(2-Fluorobenzoyl)amino]-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxylic acid (22).** The title compound was prepared starting from 21 by Method C in 65% yield: mp 186-187 °C; \(^1\)H-NMR (CDCl\(_3\)) \(\delta\) 1.60-1.70 (m, 4H, cycloheptane CH\(_2\)), 1.85-1.90, 2.75-2.80 and 3.15-3.20 (m, each 2H, cycloheptane CH\(_2\)), 7.20 (dd, \(J = 8.3\) and 12.0 Hz, 1H, aromatic CH), 7.35 (dt, \(J = 0.9\) and 7.6 Hz, 1H, aromatic CH), 7.55 (dq, \(J = 1.4\) and 7.3 Hz, 1H, aromatic CH), 8.20 (dt, \(J = 1.7\) and 7.8 Hz, 1H, aromatic CH), 12.25 (d, \(J = 11.0\) Hz, 1H, NH); \(^{13}\)C-NMR (CDCl\(_3\)) \(\delta\) 27.0, 27.7, 27.9, 28.6, 32.3, 112.8, 116.3 (d, \(J_{CF} = 24\) Hz), 119.7 (d, \(J_{CF} = 10\) Hz), 125.0 (d, \(J_{CF} = 3\) Hz), 132.0, 132.4, 134.3 (d, \(J_{CF} = 9\) Hz), 137.5, 146.7, 159.7, 160.6 (d, \(J_{CF} = 248\) Hz), 170.4. Anal. (C_{17}H_{16}FNO_{3}S) C, H, N.

**2-[(4-Fluorobenzoyl)amino]-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxylic acid (27).** The title compound was prepared starting from 23 by Method C in 33% yield: mp 205-206 °C (dec.); \(^1\)H-NMR (CDCl\(_3\)) \(\delta\) 1.60-1.70 (m, 4H, cycloheptane CH\(_2\)), 1.85-1.90, 2.75-2.80 and 3.15-
3.20 (m, each 2H, cycloheptane CH$_2$), 7.20-7.30 and 7.95-8.05 (m, each 2H, aromatic CH), 12.00 (s, 1H, NH). Anal. (C$_{17}$H$_{16}$FNO$_3$S) C, H, N.

2-[(2-Chlorobenzoyl)amino]-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxylic acid (28). The title compound was prepared starting from 24 by Method C in 39% yield; mp 226-227 °C (dec.); $^1$H-NMR (CDCl$_3$) $\delta$ 1.60-1.70 (m, 4H, cycloheptane CH$_2$), 1.85-1.90, 2.75-2.80 and 3.15-3.20 (m, each 2H, cycloheptane CH$_2$), 7.35-7.45 (m, 3H, aromatic CH), 7.80 (d, $J = 7.5$ Hz, 1H, aromatic CH), 11.75 (s, 1H, NH). Anal. (C$_{17}$H$_{16}$ClNO$_3$S) C, H, N.

2-[(4-Chlorobenzoyl)amino]-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxylic acid (29). The title compound was prepared starting from ethyl 2-[(4-chlorobenzoyl)amino]-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxylate 25 by Method C in 29% yield; mp 208-209 °C; $^1$H-NMR (CDCl$_3$) $\delta$ 1.60-1.70 (m, 4H, cycloheptane CH$_2$), 1.85-1.90, 2.75-2.80 and 3.15-3.20 (m, each 2H, cycloheptane CH$_2$), 7.45-7.50 and 7.85-7.90 (d, $J = 8.3$ Hz, each 2H, aromatic CH), 12.00 (s, 1H, NH). Anal. (C$_{17}$H$_{16}$ClNO$_3$S) C, H, N.

2-[(4-Methoxybenzoyl)amino]-5,6,7,8-tetrahydro-4H-cyclohepta[b]thiophene-3-carboxylic acid (30). The title compound was prepared starting from 26 by Method C in 32% yield; mp 187-188 °C; $^1$H-NMR (CDCl$_3$) $\delta$ 1.60-1.70 (m, 4H, cycloheptane CH$_2$), 1.85-1.90, 2.75-2.80 and 3.15-3.20 (m, each 2H, cycloheptane CH$_2$), 3.90 (s, 3H, CH$_3$), 6.95-7.00 and 7.90-7.95 (d, $J = 8.5$ Hz, each 2H, aromatic CH), 12.00 (s, 1H, NH). Anal. (C$_{18}$H$_{19}$NO$_4$S) C, H, N.

2-[(2-Fluorobenzoyl)amino]-5,6-dihydro-4H-cyclopenta[b]thiophene-3-carboxylic acid (36). The title compound was prepared starting from ethyl 2-[(2-fluorobenzoyl)amino]-5,6-dihydro-4H-cyclopenta[b]thiophene-3-carboxylate 35 by Method C in 63% yield; mp 219-220 °C; $^1$H-NMR (DMSO-$d_6$) $\delta$ 2.25 (quintet, $J = 7.5$ Hz, 2H, cyclopentane CH$_2$), 2.80 (q, $J = 7.5$ Hz, 4H, cyclopentane CH$_2$), 7.35-7.45 (m, 2H, aromatic CH), 7.70 (dq, $J = 1.4$ and 7.3 Hz, 1H, aromatic CH), 8.00 (dt, $J = 1.7$ and 7.8 Hz, 1H, aromatic CH), 12.10 (d, $J = 10.5$ Hz, 1H, NH), 13.10 (bs, 1H, COOH); $^{13}$C-NMR (DMSO-$d_6$) $\delta$ 27.8, 28.8, 30.2, 110.1, 117.2 (d, $J_{C,F} = 23$ Hz), 119.5 (d, $J_{C,F} =$
11 Hz), 125.9, 132.0, 132.6, 135.5 (d, J_C,F = 9 Hz), 142.2, 150.0, 159.3, 160.3 (d, J_C,F = 247 Hz), 166.9. Anal. (C_{15}H_{12}FNO_3S) C, H, N.

**Biology**

**Compounds and peptide.** RBV (1-D-ribofuranosyl-1,2,4-triazole-3-carboxamide) was obtained from Roche. Each test compound was dissolved in DMSO 100%. The PB1_{1-15}-Tat peptide was synthesized and purified by the Peptide Facility of CRIBI Biotechnology Center (University of Padua, Padua, Italy). This peptide possesses a C-terminal sequence from the HIV Tat protein (amino acids 47–59), which has been shown to mediate cell entry.\(^{53}\)

**Plasmids.** Plasmids pcDNA-PB1, pcDNA-PB2, pcDNA-PA, and pcDNA-NP, containing cDNA copies of the influenza A/PR/8/34 virus PB1, PB2, PA, and NP genes, respectively, were created as described elsewhere\(^{54}\) and kindly provided by P. Digard (Roslin Institute, University of Edinburgh, United Kingdom). Plasmid pPoll-Flu-ffLuc, which contains an influenza virus-based luciferase minireplicon vRNA under the control of the human RNA polymerase I promoter, was provided by L. Tiley (University of Cambridge, United Kingdom). Plasmid pRL-SV40 expressing the Renilla luciferase was purchased from Promega.

**Cells and Virus.** Human Embryonic Kidney (HEK) 293T and Mardin-Darby canine kidney (MDCK) cells were grown in Dulbecco’s modified Eagle’s medium (DMEM, Life Biotechnologies) supplemented with 10% (v/v) fetal bovine serum (FBS, Life Technologies) and antibiotics (100 U/ml penicillin and 100 µg/ml streptomycin, Life Technologies). The cells were maintained at 37 °C in a humidified atmosphere with 5% CO\(_2\). Influenza A/PR/8/34 virus (H1N1, Cambridge lineage) was obtained from P. Digard (Roslin Institute, University of Edinburgh, United Kingdom). Influenza A/Wisconsin/67/05 was provided by R. Cusinato (Clinical Microbiology and Virology Unit, Padua University Hospital, Padua, Italy). The clinical isolate A/Parma/24/09 was kindly provided by I. Donatelli (Istituto Superiore di Sanità, Rome, Italy); local strains of the new pandemic variant H1N1 FluA virus (A/Padova/30/2011, A/Padova/72/2011, and
A/Padova/253/2011) were provided by C. Salata and A. Calistri (University of Padua, Padua, Italy). Influenza B/Lee/40 virus was obtained from W. S. Barclay (Imperial College, London, United Kingdom).

**Protein expression and purification.** To obtain the 6His-PA(239-716) protein, the pET28a-PA239-716 plasmid was transformed into *E. coli* strain BL21(DE3)pLysS (Stratagene). Typically, cells were grown in Luria Bertani (LB) medium containing 50 µg/ml kanamycin until the OD$_{600}$ was 0.8 and then induced by the addition of 0.5 mM isopropyl-β-D-thiogalactopyranoside (IPTG, ICN) overnight (O/N) at 16 °C. Cells were pelleted, resuspended in 20 mM Tris-HCl pH 8.0, 500 mM NaCl, 500 mM urea, 10 mM β-mercaptoethanol, 25 mM imidazole, 1 mg/ml lysozyme, and Complete protease inhibitors (Roche Molecular Biochemicals), and then lysed by two freeze/thaw cycles and by sonication. The lysate was centrifuged at 13,000 rpm for 30 min, applied to a 0.5-ml Ni-NTA agarose resin column (Qiagen) that had been equilibrated in resuspension buffer. Protein was eluted with 20 mM Tris-HCl pH 8.0, 500 mM NaCl, 500 mM urea, 10 mM β-mercaptoethanol, 250 mM imidazole. The GST-PB1(1-25) fusion protein and GST alone were purified from *E. coli* BL21(DE3)/pLysS harboring the pD15-PB11-25 or pD15-GST plasmid, respectively. Cells were grown in LB medium containing 100 µg/ml ampicillin until the OD$_{600}$ was 0.8 and then induced by the addition of 0.5 mM IPTG O/N at 16 °C. Cells were pelleted, resuspended in 50 mM Tris-HCl pH 8.0, 150 mM NaCl, 20% glycerol, 5 mM DTT, 1 mg/ml lysozyme, and Complete protease inhibitors, and then lysed by two freeze/thaw cycles followed by sonication. The lysate was centrifuged at 13,000 rpm for 30 min, applied to a 0.5-ml glutathione-Sepharose 4 FastFlow column (Amersham Pharmacia Biotech) that had been equilibrated in lysis buffer. Finally, protein was eluted with 50 mM Tris-HCl pH 8.0, 150 mM NaCl, 20% glycerol, 5 mM DTT, and glutathione 40 mM. Both 6His-PA(239-716) and GST-PB1(1-25) purified proteins were dialyzed against 20 mM Tris-HCl pH 8.0, 150 mM NaCl, 30% glycerol, 5 mM DTT and stored at -80 °C.

**PA-PB1 interaction enzyme-linked immunosorbent assay (ELISA).** Microtiter plates (Nuova Aptca) were coated with 400 ng of purified 6His-PA(239-716) for 3 h at 37 °C and then blocked with
2% BSA (Sigma) in PBS for 1 h. After washes with PBS containing 0.3% Tween 20, 200 ng of GST-PB1(1-25), or GST alone as a control, in the absence or the presence of test compounds at various concentrations (10, 50, 100, 200 µM) were added and incubated O/N at RT. After washing, samples were incubated with horseradish peroxidase (HRP)-conjugated anti-GST monoclonal antibody (GenScript; diluted 1:3000 in PBS containing 2% FBS). Following washes with PBS plus 0.3% Tween 20, the chromogenic substrate 3,3’,5,5’ tetramethylbenzidine (TMB, KPL) was added and absorbance was read at 450 nm on an ELISA plate reader (Tecan Sunrise™).

**Cytotoxicity assays.** Cytotoxicity of compounds was tested in MDCK and HEK 293T cells by the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide (MTT) method. Briefly, cells were seeded at a density of 2×10^4 per well into 96-well plates. The next day, cell medium was removed, and fresh medium containing DMEM plus test compounds at various concentrations (from 250 to 1.9 µM) was added to each well. After 24 or 48 h for HEK 293T and MDCK cells, respectively, 5 mg/ml of MTT solution was added to each well and plates were incubated for 4 h at 37 °C in a CO2 incubator. Successively, a solubilization solution was added to lyse cells. After 3 h of incubation at 37 °C, absorbance was measured at 620 nm using an ELISA plate reader (Tecan Sunrise™).

**Plaque reduction assays (PRA).** A confluent monolayer of MDCK cells was prepared in 12-well plates. Cells were infected with the FluA or FluB virus at 40 PFU/well in DMEM supplemented with 1 µg/ml of TPCK-treated trypsin (Worthington Biochemical Corporation) and 0.14% BSA in the presence of various concentrations (0, 25, 50, 100 µM) of test compounds for 1 h at 37 °C. Medium containing 1 µg/ml of TPCK-treated trypsin, 0.14% BSA, 1.2% Avicel, and test compounds at the same concentrations was then added. After 2 days of incubation, cell monolayers were fixed with 4% formaldehyde and stained with 0.1% toluidine blue, and viral plaques were counted.

**Virus yield reduction assays.** MDCK cells were seeded at a density of 2x10^5 cells per well in 24-well plates. The next day, cells were infected with influenza A/PR/8/34 virus at an MOI of 0.01 in DMEM plus 0.14% BSA and 1 µg/ml TPCK-treated trypsin, in the presence of various
concentrations (0, 3, 10, 30, 100 µM) of test compounds for 1 h at 37 °C. Cells were then incubated
with DMEM containing 1 µg/ml of TPCK-treated trypsin, 0.14% BSA, and test compounds at the
same concentrations. At 12 h post-infection (p.i.), cell culture supernatants were collected and viral
progeny was titrated by plaque assays on MDCK monolayers.

**Minireplicon assays.** HEK 293T cells were seeded at a density of 10^5 per well into 24-well plates.
After 24 h, cells were transfected with pcDNA-PB1, pcDNA-PB2, pcDNA-PA, pcDNA-NP
plasmids (100 ng/well of each) along with pPolII-Flu-flLuc plasmid (50 ng/well). The transfection
mixture also contained pRL-SV40 plasmid (50 ng/well) to normalize variations in transfection
efficiency. Transfections were performed using calcium phosphate protocol in the presence of the
test compounds or DMSO. Cell medium was replaced 4 h post-transfection with DMEM containing
compounds or DMSO. At 24 h post-transfection, cells were harvested and both firefly luciferase
and *Renilla* luciferase expression were determined using the Dual Luciferase Assay Kit from
Promega.

**Acknowledgements**

We thank P. Digard, R. Cusinato, A. Calistri, C. Salata, I. Donatelli, and W. S. Barclay for FluA
and FluB viruses; P. Digard and L. Tiley for plasmids. We thank F. Spyrakis for computational
support. We also thank P. Digard and F. Spyrakis for helpful suggestions. This work was
supported by Italian Ministry of Health and Istituto Superiore Sanitá, Progetto Finalizzato 2009
“Studio e Sviluppo di Nuovi Farmaci Antivirali Contro Infezioni da Virus Influenzale A-H1N1” (to

**Supporting Information Available:** Table containing Elemental Analysis data for target
compounds 1-24, 26-32, and 36. This material is available free of charge via the Internet at
http://pubs.acs.org.

**Corresponding authors information:**
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   spectrum antiviral activity of Virazole: 1-beta-D-ribofuranosyl-1,2,4-triazole-3-carboxamide. 

   Egawa, H.; Minami, S.; Watanabe, Y.; Narita, H.; Shiraki, K. In vitro and in vivo activities of 


### Table 1. Structure and Biological Activity of the Compounds Synthesized in This Study.

<table>
<thead>
<tr>
<th>Compd</th>
<th>Structure</th>
<th>ELISA PA-PB1 Interaction Assay IC50, µM</th>
<th>PRA in MDCK cells EC50, µM</th>
<th>HEK 293T cells CC50, µM</th>
<th>MDCK cells CC50, µM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="Structure1.png" alt="Structure" /></td>
<td>145 ± 12</td>
<td>90 ± 13</td>
<td>&gt;250</td>
<td>&gt;250</td>
</tr>
<tr>
<td>2</td>
<td><img src="Structure2.png" alt="Structure" /></td>
<td>87 ± 11</td>
<td>&gt;100</td>
<td>&gt;250</td>
<td>&gt;250</td>
</tr>
<tr>
<td>3</td>
<td><img src="Structure3.png" alt="Structure" /></td>
<td>&gt;200</td>
<td>&gt;100</td>
<td>&gt;250</td>
<td>150</td>
</tr>
<tr>
<td>4</td>
<td><img src="Structure4.png" alt="Structure" /></td>
<td>99 ± 20</td>
<td>58 ± 7</td>
<td>&gt;250</td>
<td>&gt;250</td>
</tr>
<tr>
<td>5</td>
<td><img src="Structure5.png" alt="Structure" /></td>
<td>134 ± 21</td>
<td>39 ± 3</td>
<td>&gt;250</td>
<td>&gt;250</td>
</tr>
<tr>
<td>6</td>
<td><img src="Structure6.png" alt="Structure" /></td>
<td>32 ± 9</td>
<td>18 ± 2</td>
<td>&gt;250</td>
<td>&gt;250</td>
</tr>
<tr>
<td>7</td>
<td><img src="Structure7.png" alt="Structure" /></td>
<td>&gt;200</td>
<td>23 ± 3</td>
<td>&gt;250</td>
<td>&gt;250</td>
</tr>
<tr>
<td>8</td>
<td><img src="Structure8.png" alt="Structure" /></td>
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<td>31 ± 5</td>
<td>231 ± 7</td>
<td>&gt;250</td>
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<tr>
<td>9</td>
<td><img src="Structure9.png" alt="Structure" /></td>
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<td>20 ± 5</td>
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<td>180 ± 27</td>
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<td></td>
<td>N°</td>
<td></td>
<td>Structure</td>
<td>T (°C)</td>
<td>t (s)</td>
</tr>
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<td>----</td>
<td>----</td>
<td>---</td>
<td>-----------</td>
<td>--------</td>
<td>-------</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>“</td>
<td><img src="image1" alt="Structure" /></td>
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<tr>
<td>11</td>
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<td><img src="image2" alt="Structure" /></td>
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<td>12</td>
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<td><img src="image3" alt="Structure" /></td>
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<td>19 ± 1</td>
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<td>3</td>
<td>“</td>
<td><img src="image4" alt="Structure" /></td>
<td>&gt;200</td>
<td>17 ± 2</td>
</tr>
<tr>
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<td>3</td>
<td>“</td>
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<td>&gt;200</td>
<td>&gt;100</td>
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<tr>
<td>15</td>
<td>3</td>
<td>“</td>
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<td>18 ± 1</td>
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<tr>
<td>16</td>
<td>3</td>
<td>“</td>
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<td>21 ± 2</td>
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<td>17</td>
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<td>“</td>
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<td>58 ± 11</td>
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<td>3</td>
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<td><img src="image9" alt="Structure" /></td>
<td>90 ± 22</td>
<td>61 ± 9</td>
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<td>19</td>
<td>3</td>
<td>“</td>
<td><img src="image10" alt="Structure" /></td>
<td>35 ± 10</td>
<td>26 ± 4</td>
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<tr>
<td>20</td>
<td>3</td>
<td>NH₂</td>
<td><img src="image11" alt="Structure" /></td>
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<td>&gt;100</td>
</tr>
<tr>
<td>21</td>
<td>3</td>
<td>OEt</td>
<td>“</td>
<td>200</td>
<td>78 ± 3</td>
</tr>
<tr>
<td>22</td>
<td>3</td>
<td>OH</td>
<td>“</td>
<td>200</td>
<td>76 ± 3</td>
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<tr>
<td>23</td>
<td>3</td>
<td>OEt</td>
<td><img src="image12" alt="Structure" /></td>
<td>&gt;200</td>
<td>91 ± 10</td>
</tr>
<tr>
<td>24</td>
<td>3</td>
<td>OEt</td>
<td><img src="image13" alt="Structure" /></td>
<td>&gt;200</td>
<td>94 ± 6</td>
</tr>
<tr>
<td>25</td>
<td>3</td>
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<td><img src="image14" alt="Structure" /></td>
<td>&gt;200</td>
<td>89 ± 10</td>
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<td>26</td>
<td>3</td>
<td>OEt</td>
<td><img src="image15" alt="Structure" /></td>
<td>&gt;200</td>
<td>95 ± 5</td>
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<tr>
<td>27</td>
<td>3</td>
<td>OH</td>
<td><img src="image16" alt="Structure" /></td>
<td>&gt;200</td>
<td>81 ± 16</td>
</tr>
<tr>
<td>28</td>
<td>3</td>
<td>OH</td>
<td><img src="image17" alt="Structure" /></td>
<td>&gt;200</td>
<td>79 ± 16</td>
</tr>
<tr>
<td>29</td>
<td>3</td>
<td>OH</td>
<td><img src="image18" alt="Structure" /></td>
<td>&gt;200</td>
<td>43 ± 6</td>
</tr>
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</table>
Table 2. Activity of Selected Compounds on PR8 Virus Yield and Against Viral RNA Polymerase.

<table>
<thead>
<tr>
<th>Compd</th>
<th>Virus Yield Reduction Assay EC_{50}, µM</th>
<th>Minireplicon Assay EC_{50}, µM</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>12 ± 3</td>
<td>10 ± 2</td>
</tr>
<tr>
<td>17</td>
<td>20 ± 6</td>
<td>67 ± 10</td>
</tr>
<tr>
<td>18</td>
<td>6 ± 1</td>
<td>&gt;100</td>
</tr>
<tr>
<td>19</td>
<td>6 ± 1</td>
<td>14 ± 4</td>
</tr>
<tr>
<td>RBV</td>
<td>2 ± 1</td>
<td>15 ± 7</td>
</tr>
</tbody>
</table>

* This EC_{50} value represents the compound concentration that inhibits 50% of plaque formation.  
* This EC_{50} value represents the compound concentration that reduces by 50% the activity of FluA virus RNA polymerase in 293T cells. All data shown represent the means ± SD of data derived from at least two independent experiments in duplicate.
Table 3. Activity of Selected Compounds Against a Panel of Influenza A Virus Strains and Against Influenza B Virus.

<table>
<thead>
<tr>
<th>Virus strain</th>
<th>Compound</th>
<th>PRA (EC₅₀, µM)</th>
<th>6</th>
<th>19</th>
<th>RBV</th>
</tr>
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<tbody>
<tr>
<td>A/PR/8/34 (H1N1)</td>
<td></td>
<td>18 ± 2</td>
<td>26 ± 4</td>
<td>8 ± 2</td>
<td></td>
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<tr>
<td>A/Padova/30/2011 (H1N1)</td>
<td></td>
<td>20 ± 4</td>
<td>28 ± 5</td>
<td>7 ± 2</td>
<td></td>
</tr>
<tr>
<td>A/Padova/72/2011 (H1N1)</td>
<td></td>
<td>19 ± 2</td>
<td>22 ± 3</td>
<td>6 ± 1</td>
<td></td>
</tr>
<tr>
<td>A/Padova/253/2011 (H1N1)</td>
<td></td>
<td>21 ± 3</td>
<td>27 ± 2</td>
<td>11 ± 4</td>
<td></td>
</tr>
<tr>
<td>A/Parma/24/09 (H1N1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Oseltamivir-resistant)</td>
<td></td>
<td>23 ± 3</td>
<td>25 ± 1</td>
<td>17 ± 2</td>
<td></td>
</tr>
<tr>
<td>A/Wisconsin/67/05 (H3N2)</td>
<td></td>
<td>15 ± 1</td>
<td>19 ± 2</td>
<td>12 ± 7</td>
<td></td>
</tr>
<tr>
<td>B/Lee/40</td>
<td></td>
<td>21 ± 1</td>
<td>19 ± 1</td>
<td>6 ± 3</td>
<td></td>
</tr>
</tbody>
</table>

* The EC₅₀ value represents the compound concentration that inhibits 50% of plaque formation. All data shown represent the means ± SD of data derived from at least two independent experiments.

Figure legends

**Figure 1.** Hit compound previously identified by SBDD.

**Figure 2.** A) Hydrophobic regions generated by GRID in the PA cavity from the x-ray structure reported by He and coworkers. The best docked poses generated by FLAP for compound 1 (B), compound 17 (C) and compound 18 (D) are also reported, after mild minimization. Residues that define the first (black), the second (red), and the third (blue) cavity as defined by Liu et al. are reported. Other residues discussed in the text are reported in green.

**Figure 3.** A) Comparison between the crystallographic structure 3CM8 (light pink) and the dynamic snapshot (dark red) of PA. Hypothesis on the binding modes for compound 6 (B) and compound 19 (C) in the PA cavity as generated by FLAP, after mild minimization.
Scheme Footnotes

Scheme 1.

"Reagents and conditions: i) ammonium acetate, glacial acetic acid, benzene, reflux; ii) sulphur, \(N,N\)-diethylamine, EtOH, 40-50 °C; iii) acyl chlorides, pyridine; iv) \(\text{ArCH}_2\text{CO}_2\text{H}, \text{DMTMM, THF, pyridine.}

Scheme 2.

"Reagents and conditions: i) acyl chlorides, pyridine; ii) \(\text{LiOH, H}_2\text{O/THF, 50 °C.}

Figure 1

![compound 1](image-url)
Scheme 1

\[
\begin{align*}
\text{O} & \quad \text{CN} & \quad \text{NH} \\
\text{C} & \quad \text{N} & \quad \text{N}
\end{align*}
\]

\(n = 1, 2, 3\)

\[\text{O} \quad \text{CN} \quad \text{CN} \quad \text{NH}_2 \quad \text{R} \quad \text{NH}
\]

\(19 \quad n = 3\)

\(31 \quad n = 2\)

\(32 \quad n = 1\)

\text{for R, see Table 1}

Scheme 2

\[
\begin{align*}
\text{O} & \quad \text{R} \quad \text{C} \\
\text{O} & \quad \text{O} \quad \text{C}
\end{align*}
\]

\(n = 3, R' = \text{NH}_2\)

\(n = 3, R' = \text{NH}_2\)

\(n = 2, R' = \text{NH}_2\)

\(n = 1, R' = \text{NH}_2\)

\(22, 27-30 \quad n = 3\)

\(36 \quad n = 1\)

\text{for R, see Table 1}
Structural Investigation of Cycloheptathiophene-3-carboxamide Derivatives Targeting Influenza Virus Polymerase Assembly

Serena Massari, Giulio Nannetti, Laura Goracci, Luca Sancineto, Giulia Muratore, Stefano Sabatini, Giuseppe Manfroni, Beatrice Mercorelli, Valentina Cecchetti, Marzia Facchini, Giorgio Palù, Gabriele Cruciani, Arianna Loregian, Oriana Tabarrini

Flu RNA polymerase

PA
PB1
PB2