**N,O-Nucleoside Analogues: Metabolic and Apoptotic Activity**

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Two new families of N,O-nucleoside analogues containing the anthracene moiety introduced through the nitrosocarbonyl ene reaction with allylic alcohols were prepared. The core structure is an isoxazolidine heterocycle that introduces either atom either a phenyl ring or dimethyl moiety at the C3 carbon.

Different heterobases were inserted at the position 5 of the heterocyclic ring. One of the synthesized compounds demonstrated a good capacity to induce cell death and an appreciable nuclear fragmentation was evidenced in treated cells.

1. Introduction

Isoxazolidines are privileged heterocyclic structures that find numerous applications in organic synthesis and in medicinal chemistry specifically.[1] The ene reactions of aromatic nitrosocarbonyl[2] intermediates 1 with allylic alcohols offered an alternative pathway for the synthesis of isoxazolidines, which were found valuable synths to N,O-nucleoside analogues.[3] This methodology relies upon the mild oxidation of aromatic nitrile oxides with tertiary amine N-oxides to generate the nitrosocarbonyl intermediates 1.[4] When these intermediates are *in situ* generated in the presence of the reactive allylic alcohols 2, they undergo ene reaction.[5] The reactions proceed to the ene adducts in accordance with the prevailing HOMO(alkanol)-LUMO(nitrosocarbonyl) interaction, somewhat enforced by the polarization of the C=C double-bond induced by the slightly electron withdrawing group CH$_2$OH.[6] When sterically demanding nitrosocarbonyl mesitylene 1M (M = Mesityl), the Markovnikov (M) directing effect is relieved and the anti-Markovnikov (AM) pathway becomes competitive and the preferred one. The selectivity drift is further increased when the bulkier anthracene nitrosocarbonyl intermediate 1A (A = Anthryl) is used.[3,7]

The AM route preludes to the enol formation and subsequent cyclization to the isoxazolidines 3, which are the synths for the preparation of libraries of N,O-nucleosides 4 containing uracils and purines heterobases inserted by adapting to the scope the Vorbrüggen protocol (Scheme 1).[8]

In a previous work, we investigated the metabolic and induced cell death by apoptosis of a family of 6-chloropurine N,O-nucleoside analogues derived from the ene reaction of the cinnamyl alcohol and the mesityl nitrosocarbonyl intermediate 1M.[9] Among the various 6-chloropurine regio- and stereoisomers obtained through the Vorbrüggen derivatization of the 5-acetoxy-isoxazolidine 5, it was demonstrated that compound 6a, showing the 6-chloropurine ring *cis*-related to the phenyl ring of the isoxazolidine moiety, was more cytotoxic than that the corresponding 6b in the pro-apoptotic, metabolic and cytotoxic activities, tested on the human monocytoid U937 and the lymphoblastoid MOLT-3 cell lines (Scheme 2). Collectively, the induction of apoptosis and/or the inhibition of metabolic activity

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**Scheme 1.** Ene reaction of nitrosocarbonyl intermediates 1 with allylic alcohols 2: synthetic pathway toward isoxazolidine N,O-nucleoside analogues.

**Scheme 2.** Synthesis through Vorbrüggen protocol of the compounds 6a, b and superimposed DFT calculated structures.
and cytotoxic activity of the tested compounds at 10 μM were similar to that exhibited by the positive control Etoposide.

In terms of structure-activity relationship (SAR) it was hypothesized that the stoichiometric structure including the substitution of chlorine atom versus nitrogen associated to phenyl group in cis and or in trans might influence the apoptotic and metabolic activity of the compounds toward U937, MOLT-3 cells and normal tissues.

On pursuing our research on this field, we have synthesized two new families of N,O-nucleoside analogues (Figure 1) which contain the anthracene moiety in place of the mesityl; in the group of compounds (A) the phenyl ring is maintained at the C3 isoxazolidine moiety while in the group (B) two methyls are inserted.

At the heterobases level, both the groups contain the 6-chloropurine ring for comparison with the data already known[9] and pyrimidine- and purine-types bases are also included. The biological assays will furnish further details on the SAR for these types of isoxazoline analogues.

2. Results and Discussion

2.1. Cinnamyl Alcohol Derivatives

Addition of a dichloromethane (DCM) solution of anthracenemide oxide 7 to a stirred solution of N-methyl-morpholine N-oxide (NMO, 1.2 equiv.) in DCM in the presence of an excess (5 equiv.) of trans-cinnamyl alcohol afforded, after 48 h at room temperature, the ene adduct 8 that was isolated upon chromatographic purification from the reaction mixture in 44% yield (Scheme 1), as inseparable mixture of diastereoisomers.

Besides the excess of cinnamyl alcohol, from the reaction mixture consistent portions of non-identified anthracene derivatives were collected, as a result of decomposition of the nitrosocarbonyl intermediate 1A[10].

The structure of the 5-hydroxy-isoxazolidine 8 relies upon the corresponding analytical and spectroscopic data. In the IR spectrum the hydroxyl group gives a band at 3195 cm⁻¹ while the carbonyl group C=O was found at 1637 cm⁻¹. The NMR spectra reveal that the product is a mixture of diastereoisomers and the relative signals do not give coalescence upon increasing the experiment temperature. In particular, in the ¹H NMR spectrum (DMSO) the hemiacetal proton is clearly found at δ 5.40 while the benzylic proton is observed at δ 5.83 for the major component of the 3:1 mixture of diastereoisomers. The definitive confirmation of the structure of 8 came from the X-ray analysis and Figure 2 reports the ORTEP view of the compound.

The ene adduct 8 was then acetylated according to the established procedure[11] and compound 9 was obtained in 98% yield as a mixture of diastereoisomers in a nearly 4:1 ratio. The structure of 9 was confirmed by the relative spectroscopic data; in the ¹H NMR spectrum (DMSO), the acetate group is clearly show by the singlet at δ 1.55 corresponding to the methyl as well as by the presence in the IR spectrum of the C=O band at 1756 cm⁻¹ and the absence of the OH band. The other signals are in the expected range for the given isoxazolidine structure.

We then performed the functionalization of the isoxazoline 9 with the commercially available uracil U and thymine T by adapting the standard protocol for the insertion of heterobases on isoxazolinedine rings.[8,9] The acetylated isoxazoline 9 was added under nitrogen atmosphere at r.t. to a solution of uracil U or thymine T (2.2 equiv.) and BSA (4 equiv.) and the solutions became clear after boiling in DCM for a couple of hours. The mixtures were then ice-cooled at 0 °C and TMS-OTf (4 equiv.) was added and the reactions refuxed overnight (Scheme 4).

The desired compounds 10a, b (U, T) were obtained in good yields by chromatographic separation of the diastereomeric mixtures and fully characterized through their analytical and spectroscopic data. The relevant spectroscopic and physical-chemical data are gathered in Table 1 and details can be found in the experimental section. Compounds 10a, b (U, T) are diastereoisomers of racemic mixtures and structurally can be
divided into two series: cis, 10a (U, T) show the heterobase on the same side of the phenyl ring; trans, 10b (U, T) show the heterocyclic and phenyl rings on opposite sides with respect to the isoxazolidine moieties (Figure 3).

The stereochemical features were established through NOESY experiments and Figure 3 reports the correlations between the protons located on the carbons C3, C4 and C5 of the isoxazolidine moieties that are responsible for the stereochemical outcome. In all the cases the relative position of the benzylic protons and methylene protons allowed for the correct determination of the stereochemistry of the products as a consequence of the possible correlation with the acetalic protons.

An analogous synthetic procedure was applied for the preparation of the 6-chloropurine adducts. The acetylated isoxazolidine 9 was added under nitrogen atmosphere at r.t. to a solution of 6-chloropurine (2.2 equiv.) and BSA (4 equiv.) and the solutions became clear after boiling in DCM for a couple of hours. The mixtures were then ice-cooled at 0°C and TMS-OTf (4 equiv.) was added and the reactions refluxed overnight (Scheme 5).

The desired compounds 11a–d were obtained as white solids separated by column chromatography. The purine nucleoside analogues 11a–d were isolated in fair yields (range 22–36%). On the basis of previous observations, the reaction gave a mixture of four isomeric products where the purine ring can be linked at the isoxazolidine moiety through the N7 and/or N9 nitrogen atoms.

The structures of compounds 11a–d were attributed on the basis of the corresponding analytical and spectroscopic data and Table 2 collects the relevant physical-chemical and spectroscopic data.

### Table 1. Yields, physical-chemical and spectroscopic data of compounds 10a, b (U, T).

| Compound | m.p. [°C][a] | Yield [%] | IR νC=O [cm⁻¹] | ¹H NMR [δ, DMSO] | CH=CH=CH=NH |
|----------|-------------|-----------|-----------------|----------------|----------------|
| 10aU     | 166 (dec)   | 49        | 1698, 1708      | 5.46 (d)       | 7.87 (d)       |
| 10aT     | > 250 (dec) | 40        | 1698            | 1.53 (s)       | 7.66 (s)       |
| 10bU     | > 250 (dec) | 52        | 1693, 1716      | 5.75 (d)       | 7.93 (d)       |
| 10bT     | 171–175     | 49        | 1698, 1700      | 1.95 (s)       | 7.72 (s)       |

[a] White crystals from ethanol.

### Table 2. Yields, physical-chemical and spectroscopic data of 6-chloropurine compounds 11a–d.

| 11     | m.p. [°C][a] | Yield [%] | IR νC=O [cm⁻¹] | ¹H NMR [δ, DMSO] | H–CH=N | H–CH=N |
|--------|-------------|-----------|----------------|----------------|--------|--------|
| a      | 200–201     | 22        | 1592/1654      | 6.59 (t)       | 8.51   | 8.69   |
| b      | 201–205     | 36        | 1595/1633      | 6.56 (d)       | 8.65   | 8.89   |
| c      | 145 (dec)   | 24        | 1652/1714      | 6.55 (d)       | 8.32   | 9.06   |
| d      | 230 (dec)   | 24        | 0000/1654      | 6.67 (t)       | 8.50   | 9.48   |

[a] White crystals from iPr₂O/EtOH.
These data confirm that the 6-chloropurine ring replaced the acetate group of the starting material 9 but say little on the stereochemical arrangements of the products.

Compounds 11a–d are diastereoisomers of racemic mixtures and structurally can be divided into two series: cis, 11a, b show the 6-chloropurine on the same side of the phenyl ring; trans, 11c, d show the heterocyclic and phenyl rings on opposite sides with respect to the isoaxazoline moieties (Figure 4). Compounds 11a and 11b differ for the orientation of the purine ring, being the first linked through the N9 nitrogen atom to the isoaxazoline ring and the second through the N7 nitrogen atom. The same connections to the isoaxazoline ring are found in compounds 11c and 11d.

These two different stereo- and regiochemical aspects were solved by performing different NMR experiments. NOESY experiments allowed for the correct assignment of the stereochemical outcome of the reaction and Figure 4 reports the correlations between the protons located on the carbons C3, C4 and C5 of the isoaxazoline moieties. The relative position of the benzylic protons and methylene protons allowed for the correct determination of the stereochemistry of the products as a consequence of the possible correlation with the acetalic protons.

To determine the correct orientation of the purine ring, HMBC and HSQC NMR experiments were conducted and positive correlations were found just in some cases. Within the trans series of products, in compound 11c the acetalic proton at δ 6.55 correlates with the carbon atom at δ 151.3 (annotated with a red dot in Figure 4). This carbon atom also correlates with both the H–CH=N protons of the purine ring at δ 8.32 and 9.06 ppm. In compound 11d the acetalic proton at δ 6.67 correlates with the carbon atom at δ 121.3 that also correlates with just one of the H–CH=N protons of the purine ring. In this way the N7 and N9 orientations are determined. Within the cis series, the structure attribution of compound 11b was consequently attributed as shown in Figure 4 along with that of 11a.

2.1.1. 3-Methyl-2-buten-1-ol derivatives

The isoaxazolidine 12, prepared according to reported procedure,[3,12] was derivatized with the commercially available purine, 6-chloropurine and benzoimidazole rings by adapting the standard protocol for the insertion of heterobases on isoaxazolidine rings.[3,9,12] The acetylated isoaxazolidine 12 was added under nitrogen atmosphere at r.t. to a solution of 2.2 equiv. of the selected heterobases and BSA (4 equiv.) and the solutions became clear after boiling in DCM for a couple of hours. The mixtures were then ice-cooled at 0°C and TMSO–TF (4 equiv.) was added and the reactions refluxed overnight (Scheme 6).

In the reaction with the simple purine, two products were obtained as a racemic mixture, 13a, b (yields: 51% and 45%, respectively); they differ by the N7 and N9 orientation of the purine ring. Their structures were determined on the basis of the corresponding analytical and spectroscopic data. In particular the 1H NMR spectrum (DMSO) of compound 13a shows the acetalic proton at δ 6.86 is a double doublet, coupled with the adjacent methylene of the isoaxazolidine ring and the singlets corresponding to the purine ring are also found at δ 8.62 and 8.75. The N7/N9 orientation in compound 13a was determined by X-ray analysis and Figure 5 reports the ORTEP view of the compound.

In the 1H NMR spectrum (DMSO) of compound 13b the acetalic proton is found at δ 6.80 (dd), coupled with the adjacent methylene of the isoaxazolidine ring and the singlets corresponding to the purine ring are also found at δ 8.59 and 8.69, with the reversal orientation of the purine ring with respect to 13a.

Scheme 6. Synthesis of isoaxazolidine nucleoside analogues 13a, b, 14a, b and 15 through Vorbrüggen protocol.

Figure 4. Structure of compounds 11a–d and NOE correlations. Values in parentheses are chemical shifts (δ, ppm) of the protons giving NOE correlations (indicated by the arrows). In red the HMBC and HSQC correlations between H and C atoms are annotated with relative chemical shifts.

Figure 5. X-ray structure of compound 13a. π-Stacking between aromatic ring is indicated by red dots (centroids) with distance (3.69 Å).
Similarly, the reaction with the 6-chloropurine gives two racemic products with different regiochemical orientation of the purine ring $14a, b$ in 56% and 40% yields, respectively. The structures were attributed on the basis of the relative analytical and spectroscopic data as well as specific NMR experiments for determining the regiochemical orientation of the products.

NOESY and HMBC experiments (DMSO) allowed for the definition of the regiochemical outcome. As shown in Figure 6, the acetalic proton of compound $14a$ is clearly defined for its stereochemistry with respect to the methylene and methyl protons. Furthermore, the acetalic proton at $\delta 6.42$ correlates in the HMBC experiment with both the carbon atoms at $\delta 145.4$ and 151.3, relative to the $H-CH=N$ protons ($\delta 8.53$ and 9.75). On the other side, the acetalic proton of compound $14b$ found at $\delta 6.48$ does not correlate efficiently with none of the same carbon atoms. The structures are consequently defined.

Finally, the benzoimidazole derivative $15$ was obtained as single product in 40% yield and fully characterized. In the $^1H$ NMR spectrum (DMSO) the acetalic proton was found at $\delta 6.48$ and the $H-CH=N-R$ proton at $\delta 8.43$.

2.1.2. Biological assays

Samples of compounds $10a, b$ (U, T), $11a-d$, $13a, b$, $14a, b$ and $15$ were subjected to biological assays to assess their metabolic and pro-apoptotic activities. For the scope of the human monocytic cell line U937, was grown in RPMI (Life Technologies, Paisley, UK) supplemented with 10% heat-inactivated fetal bovine serum (FBS; Life Technologies), 2 mM glutamine (HyClone, Cramlington, UK), 50 U/ml penicillin and 50 U/ml streptomycin (HyClone). The metabolic inhibition was evaluated by MTS assay. Inhibition of cell metabolite activity was detected through formazan product formation, using a commercial colorimetric kit (MTS [3,4-(5-dimethylthiazol-2-yl)-5-(3-carboxymethoxyphenyl)-2(4-sulfophenyl)-2H-tetrazolium salt]).

Apoptosis was detected by microscopy analysis of cellular (apoptotic bodies) or nuclear (chromatin condensation, nuclear fragmentation) apoptotic morphology following Hoechst 33342 staining. For compound $11a$, also cell viability was assessed through Trypan Blue exclusion assay.

Concerning the biological activity of compounds $10a, b$ (U, T), $11a-d$, $13a, b$, $14a, b$ and $15$, a dose effect assay using three or four different concentrations of the compounds, within the range from 100 to 1.56 $\mu M$, assessed the metabolic inhibitory activity, expressed as IC50, showing that the diastereoisomers $10a, b$ (U, T), were endowed with a high IC50 except for $10b$ T. Conversely, the compounds $11a-d$ were more effective in inhibiting the metabolic activity, showing lower IC50 values (Table 3).

Interestingly, compounds $11a, b, c$ were also able to induce appreciable levels apoptosis, showing lower CCG50 values in comparison with $10a, b$ (U, T), being $11a$ the most potent apoptosis inducer. Compounds $13, 14$ and $15$ showed lack of metabolic inhibitory activity or ability to induce apoptosis except for $15$, which exhibited IC50 and CCG50 values similar to that of $11a-d$ compounds. Thus, the comparative analysis of the biological activities of the different diastereoisomer series, compound $11a$ was found the most effective one exerting, in particular, a remarkable pro-apoptotic activity. We then focused our attention on the capacity of compound $11a$ to induce cell death by comparing in details its ability to induce apoptosis, as assessed by Hoechst staining, with its ability to induce also other forms of cell death, as assessed by Trypan blue exclusion assay, at different concentrations after 18 hours (Table 4).

The results, expressed as percentage of Trypan blue positive and apoptotic cells $\pm$ SD, show that increasing concentrations of $11a$ led to increased percentages of both Trypan blue and apoptotic cells, being the former always lower than the latter. This implies that apoptosis was the exclusive form of cell death induced by $11a$ treatment.

As an example, Figure 7 shows the nuclear morphology of apoptotic cells after treatment with $11a$. Vehicle treated U937 cells showed few sporadic apoptotic nuclei (Figure 7a). Conversely, following treatment with 6.25 and 25 $\mu M$ $11a$ (Figure 7b and 7c, respectively), an evident increase of fluorescence, due to increased stain absorption by condensed chromatin, and...
Table 4. Effects of compound 11a on cell death, as assessed by the Trypan blue dye exclusion test and by microscopy detection of apoptosis in U937 cells.

| Compound concentration [μM] | % Trypan Blue positive cells ± SD | % Apoptotic cells ± SD |
|-----------------------------|-----------------------------------|------------------------|
| CTR[9]                      | 3.69 ± 1.70                       | 4.47 ± 1.53            |
| 1.56                        | 10.22 ± 1.45                      | 11.43 ± 0.81           |
| 3.12                        | n.d.[9]                           | 13.27 ± 1.62           |
| 6.25                        | 14.32 ± 1.24                      | 17.53 ± 3.29           |
| 25                          | 29.28 ± 6.09                      | 73.97 ± 6.90           |
| 50                          | 36.11 ± 8.24                      | n.d.[9]                |

[a] Apoptotic cells as detected by microscopy analysis of cellular (apoptotic bodies) or nuclear (chromatin condensation, nuclear fragmentation) apoptotic morphology following Hoechst 33342 staining. [b] Values obtained in cells treated with vehicle alone (DMSO) at the highest concentration utilized to dilute the compound. [c] n.d. = not done.

Figure 7. Fluorescence microscopy images of representative slides showing the effects of 11a treatment on U937 cells. Control cells (a) and cells treated with 6.25 μM (b) and 25 μM (c) 11a were analysed at 18 h incubation after staining with 10 μM of the fluorescent DNA-binding dye Hoechst 33342. The majority of control, vehicle treated U937 cells exhibit normal nuclear morphology, with only a few sporadic cells showing signs of apoptosis. In contrast, the nuclear morphology of 11a treated cells (b and c) demonstrated intense fluorescence resulting from increased stain absorption by condensed chromatin and visible nuclear fragmentation, characteristic of early and late apoptosis, respectively. Original magnification, 400X. Scale bar, 10 μM. Samples were analysed and captured by Observer Z1 fluorescence microscope (Zeiss, Jena, Germany).

Figure 8. Optimized structures of compounds 6a (see ref. 9: ACS Omega 2018, 3, 7621–7629) and 11a (top). Overlap of 6a and 11a (bottom).
pseudo-equatorial positions, cis-related with the phenyl rings. Both compounds are the most stable conformers and belong to the N9 derivative series, i.e. the 6-chloropurine ring is attached to the isoxazolidine ring through the N9 nitrogen atom. They are reasonably stabilized by nonclassical intramolecular purine H-bond between the H–C=O–R proton and the phenyl ring.\(^{[9]}\)

On the basis of the present as well as previous biological data, the structure comparison between compounds 6a and 11a leads to considering the structure overlap that is shown in Figure 8 (bottom) where the isoxazolidine rings were fused at the N–O heteroatoms. The resulting fitting of the other parts of the two molecules is substantially excellent. While the purine and phenyl rings are slightly apart each other, the overlap of the anthryl and mesityl moieties is quite perfect. These observations corroborate the nice fitting of the biological results and represent a strong contribution in the SAR analysis.

In order to broaden the antitumor activity, we are actively pursuing new syntheses of isoxazolidine derivatives and the strategies we are following are summarized in Figure 9. We wish to clarify the roles of the three main substituents around the isoxazolidine ring. First, we will replace the chlorine atom on the purine ring aiming to verify the role of the Cl atom itself and the potential effect of replacement with nitrogen, oxygen or other. Second, the substituent at the position C3 of the isoxazolidine ring seems to be a key element and needs to be verified by deleting the substituent and leaving on the heterocyclic ring a simple methylene group.\(^{[10]}\) Third and finally, the aromatic moieties linked to the carbonyl group are normally characterized by a not negligible steric demand due to the nitrosocarbonyl ene reaction mechanism that requires the activation of the anti-Markovnikov pathway through steric effects.\(^{[2,3]}\) For these reasons we plan to modify the synthetic approach for the insertion of simple phenyl rings on some isoxazolidine derivatives and even simple aliphatic substituents to shine some light on the role of this portion of the molecule in the biological activity. This last point will be pursued by means of catalyzed syntheses between hydroxamic acids and unsaturated aldehydes.\(^{[4]}\)

3. Conclusions

In conclusion, we have synthesized two new families of N,O-nucleoside analogues (Figure 10) which contain the anthracene moiety introduced through the nitrosocarbonyl ene reaction with allylic alcohols, using the stable anthracenitrile oxide as synthon of the fleeting intermediate; in the group of compounds (A) the phenyl ring is maintained at the C3 isoxazolidine moiety while in the group (B) two methyls were inserted.

At the heterobase level, both the groups of isoxazolidines were functionalized with the 6-chloropurine ring for comparison with the data already known.\(^{[9]}\) Pyrimidines and other bases were also included to expand the scope of the synthesis and the biological frame.

From the synthetic point of view, the methodology was found to be robust and reliable and gave the desired products in good yields. The structures were definitively demonstrated on the basis of analytical and spectroscopic data as well as specific experiment that contributed in the stereochemical definition of every single compound. X-Ray diffractometric analyses also corroborated the spectroscopic attributions.

Biological assays were conducted to investigate the metabolic and pro-apoptotic activities of the designed compounds. Compound 11a demonstrated a good capacity to induce cell death and an appreciable nuclear fragmentation was evidenced in cells treated with 11a.

These results nicely fit with some previous observations\(^{[9]}\) regarding the role of the heterobases and the relative stereochemistry with substituents in C3 of the isoxazolidine ring and these SAR observations pave the way to further studies that require the synthesis of new compounds, even through different synthetic methods already located in our research activities.

We are confident in gaining rapidly new results able to give the isoxazolidine derivatives a solid background as antitumor promoters.\(^{[12]}\)

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**Figure 9.** SAR: structural modifications on the 11a scaffold.

**Figure 10.** Synthesized nucleoside analogues; compound 11a.
Experimental Section

All melting points (m.p.) are uncorrected. Elemental analyses were done on an elemental analyzer available at the Department. 1H and 13C NMR spectra were recorded on a 300 MHz and 400 MHz spectrometers (solvents specified). Chemical shifts are expressed in ppm from internal tetramethylsilane (δ) and coupling constants (J) are in Hertz (Hz): b, broad; s, singlet; bs, broad singlet; t, doublet; t, triplet; q, quintet; m, multiplet. IR spectra (nujol mulls) were recorded on a spectrophotometer available at the Department and absorption υ are in cm⁻¹. Column chromatography and tlc: silica gel H60 and GF₄₅, respectively; eluants: cyclohexane/ethyl acetate 9:1 to pure ethyl acetate; when specified, pure CHCl₃ to CHCl₃/MeOH 9:1 for the nucleosides syntheses.

Starting and Reference Materials: Cinnamyl alcohol (98%) and 3-methyl-2-buten-1-ol (99%) were purchased from chemical suppliers and used without any further purification. Other reagents and solvents were purchased from chemical suppliers.

Alcohol 10a, b (U, T) by Coupling of Isoxazolide 9 and Uracil and Thymine: A solution of 2.2 equiv. of uracil or thymine and 4 equiv. of bis(trimethylsilyl)acetamide (BSA) in anhydrous DCM (50 mL) is refluxed under nitrogen atmosphere for 1 h. A solution in DCM (10 mL) of isoazolidine 9 (0.40 g, 0.97 mmol) is added dropwise and cooled to 0 °C and addition of 4 equiv. of TMSO–Tf. The reaction is refluxed under stirring overnight and finally quenched with a saturated solution of NaHCO₃ at pH = 7. The mixture is diluted with an equivalent volume of DCM and washed with water and finally dried over Na₂SO₄. From the residues, nucleosides 10a, b (U, T) are isolated through column chromatography and fully characterized.

Synthesis of Nucleosides 10a, b (U, T) by Coupling of Isoxazolide 9 and Uric Acid or Thymidine: A solution of 2.2 equiv. of uric acid or thymidine and 4 equiv. of bis(trimethylsilyl)acetamide (BSA) in anhydrous DCM (50 mL) is refluxed under nitrogen atmosphere for 1 h. A solution in DCM (10 mL) of isoazolidine 9 (0.40 g, 0.97 mmol) is added dropwise and cooled to 0 °C and addition of 4 equiv. of TMSO–Tf. The reaction is refluxed under stirring overnight and finally quenched with a saturated solution of NaHCO₃ at pH = 7. The mixture is diluted with an equivalent volume of DCM and washed with water and finally dried over Na₂SO₄. From the residues, nucleosides 10a, b (U, T) are isolated through column chromatography and fully characterized.
The mixture is diluted with an equivalent volume of DCM and washed with water and finally dried over Na₂O₃. From the residues, nucleosides 11-18 are isolated through column chromatography and fully characterized.

**Compound 11a:** Yield 0.11 g (22%). M.p. 200–201°C (iPr₂O/EtOH).
IR: ν = 1592 (C=O), 1654 (C=O) cm⁻¹.
1H NMR (300 MHz, [D6]DMSO, 25°C): δ = 3.42 (m, 1H, CH), 6.34 (m, 1H, CH), 6.26 (6t, 1H, J = 8 Hz, CH–Ph), 6.59 (1H, J = 6 Hz, CH), 7.45–7.85 (m, 1H, CH, Ar), 8.13 (1H, J = 8 Hz, CH–Ph), 8.67 (1H, J = 8 Hz, O–CH), 7.09 (m, 1H, CH, Ar), 7.45–7.85 (m, 10H, arom.), 8.13 (1H, J = 8 Hz, Ar), 8.50 (s, 1H, H N), 130.4 (2H, CH–Ph), 130.6 (3H, CH–Ph), 140.1 (4H, CH–Ph), 142.0, 148.1, 152.3, 161.5, 168.8.
C₇H₃ClIN₂O₅ (505.96): calcld. C 68.84, H 3.98, N 13.84; found C 68.85, H 3.96, N 13.86.

**Compound 11b:** Yield 0.18 g (36%). M.p. 201–205°C (iPr₂O/EtOH).
IR: ν = 1595 (C=O), 1633 (C=O) cm⁻¹.
1H NMR (400 MHz, [D6]DMSO, 25°C): δ = 3.43 (m, 1H, CH), 4.00 (m, 1H, CH), 6.31 (t, 1H, J = 8 Hz, CH–Ph), 6.56 (d, 1H, J = 7 Hz, CH), 7.67 (m, 2H, CH, Ar), 7.21 (2H, 1H, CH, Ar), 7.46–7.84 (m, 9H, arom.), 8.10 (1H, J = 8 Hz, CH–Ph), 8.32 (1H, J = 8 Hz, CH, Ar), 8.52 (s, 1H, CH, Ar), 9.06 (s, 1H, H N, Ar). 13C NMR (75 MHz, [D6]DMSO, 25°C): δ = 40.1, 60.4, 62.2, 121.9, 124.1, 125.1, 125.6, 125.8, 126.4, 127.1, 127.4, 127.9, 128.3, 128.7, 129.0, 129.5, 130.4, 130.6, 140.1, 142.0, 148.1, 152.3, 161.5, 168.8.
C₇H₂ClIN₂O₅ (505.96): calcld. C 68.84, H 3.98, N 13.84; found C 68.82, H 3.97, N 13.83.

**Compound 12:** Yield 0.12 g (24%). M.p. 230°C (dec.) (iPr₂O/EtOH).
IR: ν = 1652 (C=O), 1714 (C=O) cm⁻¹.
1H NMR (300 MHz, [D6]DMSO, 25°C): δ = 3.07 (m, 1H, CH), 4.90 (m, 3H, CH, Ar), 6.38 (1H, J = 8 Hz, CH–Ph), 6.55 (1H, J = 7 Hz, CH), 6.77 (m, 2H, CH, Ar), 7.21 (2H, 1H, CH, Ar), 7.46–7.84 (m, 9H, arom.), 8.10 (1H, J = 8 Hz, CH–Ph), 8.32 (1H, J = 8 Hz, CH, Ar), 8.52 (s, 1H, CH, Ar), 9.06 (s, 1H, H N, Ar). 13C NMR (75 MHz, [D6]DMSO, 25°C): δ = 40.9, 58.8, 83.8, 122.0, 124.2, 124.6, 125.5, 125.8, 126.4, 126.9, 127.3, 127.9, 128.0, 128.1, 128.7, 129.1, 129.9, 130.2, 131.4, 141.1, 145.1, 149.3, 151.27, 151.3, 165.9.
C₇H₂ClIN₂O₅ (505.96): calcld. C 68.84, H 3.98, N 13.84; found C 68.82, H 3.97, N 13.83.

**Synthesis of Nucleosides 13-15 by Coupling of Isoxazolidine 12 and Purine, 6-Chloropurine and Benzoimidazole:** A solution of 2.2 equiv. of 6-chloropurine and 4 equiv. of bis(trimethylsilyl) acetamide (BSA) in anhydrous DCM (50 mL) is refluxed under nitrogen atmosphere for 1 hour. A solution in DCM (10 mL) of isoxazolidine 12 (0.50 g, 1.38 mmol) is added dropwise and cooled to 0°C and additional of 4 equiv. of TMSO–TiF. The reaction is refluxed under stirring overnight and finally quenched with a saturated solution of NaHCO₃ at pH = 7. The mixture is diluted with an equivalent volume of DCM and washed with water and finally dried over Na₂O₃. From the residues, nucleosides 13-15 are isolated through column chromatography and fully characterized.

**Compound 13a:** Yield 0.30 g (51%). M.p. > 200°C (dec.) (MeOH).
IR: ν = 1574 (C=O), 1634 (C=O) cm⁻¹.
1H NMR (300 MHz, [D6]DMSO, 25°C): δ = 1.18 (s, 3H, CH₃), 2.21 (3H, CH₃), 3.07 (1H, H–CH), 3.53 (1H, H–CH₂), 6.45 (1H, arom.), 6.86 (dd, 1H, J = 8 Hz, O–CH–N), 7.24 (1H, arom.), 7.46 (1H, arom.), 7.57 (2H, arom.), 7.89 (2H, arom.), 8.09 (1H, arom.), 8.53 (s, 1H, CH–N), 8.62 (s, 1H, CH–N), 8.75 (s, 1H, CH–N), 9.08 (s, 1H, arom.), 164.5. C₇H₃ClIN₂O₅ (421.50): calcld. C 76.94, H 5.50, N 9.97; found C 76.95, H 5.48, N 10.00.

**Biological Assays**
Human monocytic U937 cells, originally obtained from the Istituto Zooroepatologia, Brescia (Italy) were cultured at 37°C in a 5% CO₂ incubator. For detection of metabolic activity by the MTS assay and of cell death by the Trypan blue dye exclusion test, standard methods were utilized. For detection of apoptosis following Hoechst 33342 staining, fluorescence microscopy analysis was performed as previously described. [H]
ICONS and CC$_{25}$ values were calculated using the (MLA) "Quest Graph™" Four Parameter Logistic (4PL) Curve Calculator. AAT Bioquest, Inc, 09 Jan. 2020, https://www.aatbio.com/tools/four-parameter-logistic-4pl-curve-regression-online-calculator.

**X-Ray Crystallographic Analysis of Compounds 8 and 13 a**

Unit-cell dimensions for compounds 8 and 13a were obtained by least-squares fit of 2θ values for 25 reflections, using an Enraf-Nonius CAD4 diffractometer with graphite-monochromated Mo-Kα radiation at the Centro Grandi Strumenti (CGS) of the University of Pavia, Italy.

The structure was solved by direct method and the E-map correctly revealed the non-hydrogen atoms in the molecules. The positions of the hydrogen atoms were located from a difference Fourier synthesis, compared with those calculated from the geometry of the molecules, and refined isotropically in the subsequent least-squares refinement. The programs SHELXL[19] is used to solve the structure. The ORTEP[20] program is used for molecular graphics.

CCDC deposition numbers: 8, 1981058; 13 a, 1981060.

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**Conflict of Interest**

The authors declare no conflict of interest.

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