European Journal of Medicinal Chemistry 44 (2009) 4266–4275

Contents lists available at ScienceDirect

European Journal of Medicinal Chemistry

journal homepage: http://www.elsevier.com/locate/ejmech

Original article

Design and one-pot synthesis of α-aminophosphonates and bis (α-aminophosphonates) by iron(III) chloride and cytotoxic activity

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ARTICLE INFO

Article history:
Received 24 January 2009
Received in revised form
17 June 2009
Accepted 9 July 2009
Available online 16 July 2009

Keywords:
α-Aminophosphonates
$FeCl_3$
Cytotoxicity
Docking

ABSTRACT

In this study, we used a solution of $FeCl_3$ in THF to facilitate the Mannich-type reaction of aldehyde, amine and phosphite compounds to form corresponding α-aminophosphonates in a one-pot, three-component reaction. Selected α-aminophosphonates were entered into a biological assay test and were studied by docking methods, using Autodock 3.0.

The results showed that the reactions were carried out mildly and eco-friendly to form α-aminophosphonates in high yields. Some were found to have cytotoxic activity on the cell lines RAJI, JURKAT and MCF-7. An indole derived bis(α-aminophosphonates) showed maximum cytotoxic effect comparable to doxorubicin. Although the FDE (Final Docking Energy) for the most cytotoxic compound was of the most negative value, there is no correlation between FDE and cytotoxicity.

1. Introduction

Organophosphorus compounds have found a wide range of applications in the areas of industrial, agricultural, and medicinal chemistry owing to their biological and physical properties as well as their utility as synthetic intermediates [1–5]. As a kind of natural amino acid analogues, α-aminophosphonates constitute an important class of compounds with diverse biological activities. The activity of α-aminophosphonates as peptidomimetics [6], enzyme inhibitors [7], pharmacogenic agents [8], haptens of catalytic antibodies [9], herbicidals [10], inhibitors of serine hydrolases [11], inhibitors of UDP-galactopyranose mutase [12] and antitumor agents [13–15] is reported in literature.

Catalytic synthetic methods that allow the limits of fine organic synthesis to be expanded considerably play a special role in synthetic organic chemistry. Catalytic methods are currently used in synthetic organophosphorus chemistry to obtain various organophosphorus compounds, in particular, functionalized phosphonates and phosphinates, which attract a special attention due to their biological activities [16]. A large number of methods for the preparation of diverse α-aminophosphonates have been published since the first synthesis by Fields [17] in 1952: addition of imines to di- or trialkyl phosphite derivatives [18], nucleophilic amination of α-hydroxyphosphonate derivatives [19], electrophilic amination of α-alkylphosphonamides [20], hydrogenation of dehydroaminophosphonate derivatives [21], aldol-type reactions of (isocyanomethyl)phosphonates with aldehydes [22], hydrogenation of aziridinylphosphonate [23], addition of phosphites to sulfimines [24] and catalyzed Mannich-type one-pot procedures [25]. However, one-pot synthesis of α-aminophosphonates remains a favor due to its versatile route and high yielding reactions. Recently, three-component synthesis starting from aldehydes, amines and diethylphosphite or triethylphosphite have been reported by using Lewis and Brønsted acid catalysts such as $LiClO_4$ [26], $InCl_3$ [27a], $ZrCl_4$ [27b], $AlCl_3$ [27b], lanthanide triflates/magnesium sulfate [28], $SbCl_3/Al_2O_3$ [29a], $TaCl_5$–SiO_2 [29b], amberlyst-15 [30a], montmorillonite clay-MW [30b], Al_2O_3-MW [31], CF_3CO_2H [32a], sulfamic acid [32b], scandium (tris-dodecyl sulfate) [33], $BF_3 \cdot Et_2O$ [34], $M(OTf)_n$ [35] and $M(ClO_4)_n$ [36]. Though, many of these methods suffer from some drawbacks such as long reaction times, low yields of the products, requiring stoichiometric amounts of catalysts, costly and moisture sensitive catalysts and use of highly toxic or toxic catalysts. More recently, $ZrOCl_2 \cdot 8H_2O$ [37] or $ZrO(ClO_4)_2 \cdot 6H_2O$ [38] and TiO_2 [39] are reported to be effective

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doi:10.1016/j.ejmech.2009.07.009

catalysts for the formation of α-aminophosphonates using a three-component system composing of aldehydes/ketones, amines and diethylphosphite under neat conditions.

$FeCl_3$ has emerged as a potential catalyst in effecting various organic transformations due to its high catalytic ability, economic viability, and easy availability [40]. However, $FeCl_3$ suffers from being hygroscopic and is also a corrosive material. These limit the use of this compound as a reagent or catalyst in organic synthesis, especially for the large-scale operation. On the other hand, dissolved $FeCl_3$ in THF (tetrahydrofuran) produces a yellow to green colour solution which can be bottled and stored at room temperature for months without being hygroscopic. Transformation of this solution to the reaction mixture is easily performed by a pipette or by an eye dropper without any serious precaution.

As a part of our continued interest in the development of synthetic methods for the preparation of phosphonate derivatives [35,41], we have found that $FeCl_3 \cdot THF$ solution catalyzes highly efficient preparation of α-aminophosphonates *via* a three-component system composing of aldehydes, amines, and diethylphosphite (Scheme 1). We have also applied this protocol for the one-pot preparation of bis(α-aminophosphonates) by the reaction of aldehydes, amines, and diethylphosphite as a three-component system. The efficient methods for the preparation of bis-(α-aminophosphonates) are rather limited in the literature (Scheme 1).

At present, cancer is the leading cause of death worldwide. It accounted for 7.9 million deaths (around 13% of all deaths) in 2007 [42]. Despite recent progresses in cancer chemotherapy, high toxicity and low specificity of current medications are motivating the scientists to search for safer and more effective anticancer drugs. Along with the extensive worldwide research, we decided to study antitumor activity of some new bis(α-aminophosphonates) to expand our survey in anticancer drug research. To the best of our knowledge, the biological studies are not extended to bis(α-aminophosphonates), yet. This group of compounds may have even more effect and range of bioactivity, due to an increased number of phosphonate and amine functionality in a unique molecule.

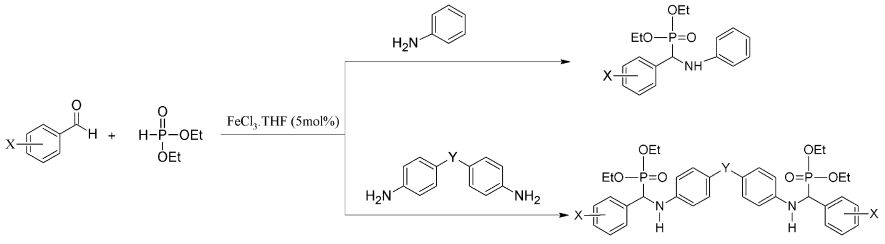
Computer docking techniques play an important role in the drug design as well as in the mechanistic study by placing a molecule into the binding site of the target macromolecule in a non-covalent fashion [43]. DOCK [44] and AutoDock [45] as flexible docking programs enable us to predict favorable protein–ligand complex structures with a reasonable accuracy and speed. These docking programs, when used prior to experimental screening, can be considered as powerful computational filters to reduce labor and cost needed for the development of potent medicinal compounds. When used after experimental screening, they can help to a better understand of bioactivity mechanisms. AutoDock is said to offer a reasonable result in comparison with other popular docking programs [46]. The docking technique will undoubtedly continue to play an important role in drug discovery [47]. Several drugs that were designed by intensive use of computational methods are currently under investigation for clinical trials [48] Therefore, we utilized AutoDock 3.0 to interpret probable mechanism of anti-proliferative action of the synthesized bis(α-aminophosphonates). The breadth and the relatively planar structure of the synthesized compounds were suggestive of intercalating properties of these bis(α-aminophosphonates). Moreover, the presence of phosphonate groups in the ends of molecule and the presence of NH in the middle of the structure tempted us to study the probable intercalating activity of the compounds. In order to find most probable intercalating agents, first we used Autodock to estimate the most negative energy of docking for all of the compounds which means the most probable ability of compounds to intercalate with DNA. Then the selected compounds were entered into a biological assay. Doxorubicin was selected as reference intercalating agents.

2. Chemistry

At the outset it was investigated the three-component reaction of benzaldehyde, aniline, and diethylphosphite in the presence of a catalytic amount of $FeCl_3 \cdot THF$ solution. The best reaction condition was resulted when the molar ratio of benzaldehyde (2.0 mmol)/aniline (2.0 mmol)/diethyl phosphate (2.2 mmol)/$FeCl_3 \cdot THF$ (1.0 mL, 5 mol%) were used at 60 °C. At this condition, the reaction proceeded well and completed after 0.75 h to produce the desired diethyl phenyl(phenylamino)-methylphosphonate (**1a**) in 95% isolated yield. The merit of the catalyst has been shown by conducting the reaction of benzaldehyde (2.0 mmol)/aniline (2.0 mmol)/diethyl phosphate (2.2 mmol) under similar conditions as mentioned above in the absence of the catalyst. The reaction did not proceed even after 24 h. In order to show the general application of the method, several aldehydes, amines and diethyl phosphate with similar molar ratios as above, were reacted smoothly for the appropriate reaction times (0.5–2 h) to yield the corresponding α-aminophosphonates in excellent isolated yields (80–95%). The examples studied cover electron-rich and electron-deficient aromatic aldehydes with aniline as an aromatic amine and also showing that *N*-methyl aniline reacts smoothly to give the corresponding α-aminophosphonate carrying a secondary amine moiety. The results are summarized in Table 1.

We have also compared the catalytic activity of $FeCl_3 \cdot THF$ with respect to the other catalysts used for the reaction of *p*-methoxybenzaldehyde and aniline with diethylphosphite as presented in Table 2.

Bis(α-aminophosphonates) are interesting compounds, as they are multidentate ligands which may be used for the extraction of metals from solutions and they can be employed as the monomers for the preparation of macrocyclic or polymeric compounds carrying phosphonate and amine moieties. In addition, and more importantly, investigation of their biological activity would be of great interest. Through this study, it was also investigated the applicability of the catalyst solution for the preparation of bis(α-aminophosphonates) *via* a one-pot three-component reaction of structurally diverse diamines (1.0 mmol), electron-rich and



Scheme 1. Three-component reaction of aromatic aldehydes with amine and diethylphosphite in $FeCl_3 \cdot THF$ solution.

Table 1
$FeCl_3 \cdot THF$ solution catalyzed synthesis of α-aminophosphonates by using a three-component system.

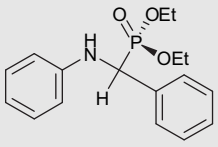
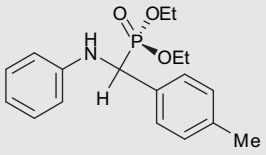
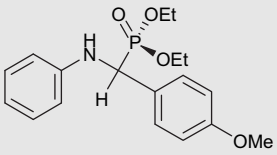
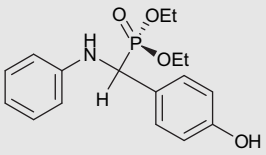
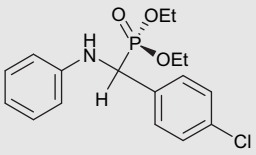
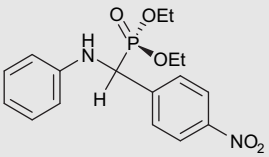
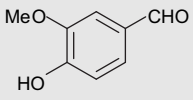
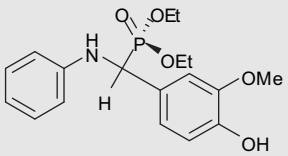
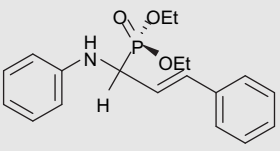
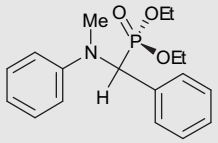
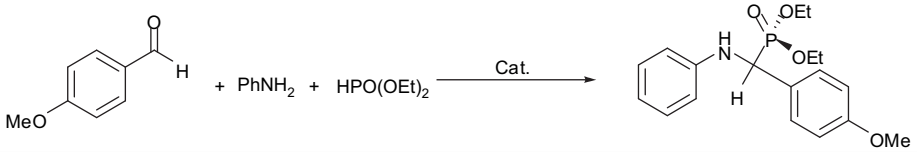
Entry	Aldehyde	Amine	α-Aminophosphonate	Time (h)	Yield (%)
1a	PhCHO	$PhNH_2$		0.75	95
1b	4-Me–PhCHO	$PhNH_2$		0.5	95
1c	4-MeO–PhCHO	$PhNH_2$		0.75	92
1d	4-HO–PhCHO	$PhNH_2$		0.5	95
1e	4-Cl–PhCHO	$PhNH_2$		1	95
1f	4-NO_2–PhCHO	$PhNH_2$		1	90
1g		$PhNH_2$		1	91
1h	PhCH=CHCHO	$PhNH_2$		2	87
1i	PhCHO	Ph(Me)NH		2	80

Table 2
Comparison of the effect of catalysts in preparation of α-aminophosphonate by the reaction of 4-methoxybenzaldehyde, aniline and diethylphosphite.



Entry	Catalyst (mol%)	Solvent	Time (h)	Yield (%)	Ref.
1	$TaCl_5$–SiO_2 (10)	CH_2Cl_2	19	88	[15]
2	$InCl_3$ (10)	THF	11	92	[13]
3	Sulfamic acid (20)	–	2	87	[18b]
4	$ZrCl_4$ (10)	CH_3CN	8.5	85	[13]
5	$AlCl_3$ (10)	CH_3CN	8.5	80	[13]
6	$SbCl_3/Al_2O_3$ and molecular sieves 5 Å (10)	CH_3CN	3.5	92	[15]
7	TiO_2 (20)	–	2.5	98	[25]
8	$Al(OTf)_3$ (10)	–	3	90	[21]
9	$Ce(OTf)_4$ (10)	–	4	78	[21]
10	$FeCl_3$ (5)	THF	0.75	92	–

electron-deficient aromatic aldehydes (2.0 mmol) and diethylphosphite (2.2 mmol) in the presence of $FeCl_3$·THF solution (2.0 mL, 5 mol%). The reactions progressed well at 60 °C and the desired bis(α-aminophosphonates) were produced in excellent isolated yields (90–95%). 1,4-Phenylenediamine also reacted successfully under similar reaction condition and the corresponding bis(α-aminophosphonates) were produced in 92% in 1 h. However, 1,2-phenylenediamine failed to react under similar reaction conditions (Table 3).

We were also interested to prepare bis(α-aminophosphonates) carrying a nucleoside moiety in a molecule. For this purpose, guanosine (a nucleoside containing guanine) was reacted with phenylene dicarboxaldehyde and diethyl phosphate under similar reaction conditions. The reaction proceeded smoothly with the cleavage of the sugar moiety of the nucleoside to produce the corresponding bis(α-aminophosphonate) **3** in a moderate isolated yield (58%) as shown in Scheme 2.

3. Molecular docking

The ligand was drawn in the Hyperchem 7.5. The geometry was optimized through the molecular dynamic method AMBER and semi-empirical method AM1. The DNA receptor structure was extracted from Protein Data Bank (PDB code 1D12). The Autodock software version 3.0.5 was used for the molecular docking process. The grids were constructed around the DNA double strands. The Lamarckian Genetic Algorithm method was used for the global optimum binding position search. A number of 80 cycles of calculation were used in order to get a final binding position as accurate as possible. The complex of ligand/DNA was viewed by Accelry's Discovery Studio Visualizer. The docking procedure was run and the maximum negative Final Docking Energy (FDE) was calculated (Table 4).

4. Biological assay

MTT assay was performed on the cell lines RAJI, JURKAT and MCF-7 which were cultivated in RPMI 1640, enriched with 10% fetal bovine serum (Gibco). All compounds tested were dissolved in DMSO and subsequently diluted in the culture medium before treatment of the cultured cells. Fresh cells were plated in 96-well plates at a density of 10^4 cells/well/100 μL of the proper culture medium and treated with the compounds at the concentrations of 0.1, 1, 10, 25, 50, 75 and 100 to maximize the precision of tests. Doxorubicin was added to individual wells of fresh cells at the same concentrations as the positive control. Treated cells were incubated in 37 °C incubator, supplemented with 5% CO_2 and 95% humidity for 48 h (RAJI, JURKAT) to 72 h (MCF-7). In parallel, the cells were treated with 0.6% of DMSO as negative control. MTT was added after the incubation period and the cells were incubated for an extra 4 h. Formazan crystals were then dissolved in 2-propanol/DMSO/HCl (30:20:2). Absorbance was read by ELISA spectrophotometer (TitertekPlus, NS2 Reader, ICN Biomedical, Canada) at 570 nm.

5. Results and discussion

5.1. Molecular docking

According to the data of FDEs, compound **2m** had the maximum negative FDE, after doxorubicin. Therefore, in the case of compound **2m**, the result of docking was in agreement with the result of biological assay. The reason of the potent cytotoxic activity of compound **2m** could be explained by taking advantage of docking results. As it is illustrated in Fig. 1, compound **2m** can be placed in the middle of the two strands of DNA double strands. The nitrogen atom of indole in one end of the molecule can make a hydrogen bond with the O_4 atom of the Tym_4 form one strand of DNA. This nitrogen can also make a hydrogen bond with the $O_{2'}$ of the deoxyribose of Cyt_5 in the same strand of DNA (Fig. 2). At the other end of the molecule, the nitrogen of NH can make a hydrogen bond with O_2 of Cyt_5 in one strand and N_2 of Gua_2 from the other strand (Fig. 3). These numerous hydrogen binding may be the reason of a probable intercalating properties and observed cytotoxicity.

Compound **2f** had $IC_{50} = 58.6$ μM for RAJI ($r^2 = 0.967$). However, the FDE of compound **2f**, that showed moderate toxicity, was less negative than some other compounds that showed no cytotoxicity. On the other hand, there were a number of compounds which had a more negative FDE than **2f**, but showed no cytotoxicity. Despite the exact reason of this controversy needs more mechanism including studies, it may be justified by limitations of docking software, incorrect selection of the ligand's target and effect of cell metabolism pathways that can activate or deactivate exotic molecules. A comparison of maximum inhibition percentage of compounds tested at 100 μM vs. Final Docking Energy is shown in Table 4.

Table 3
$FeCl_3 \cdot THF$ solution catalyzed synthesis of bis(α-aminophosphonates) by using a three-component system. In all the reactions, diethylphosphate is used to form the corresponding phosphonates.

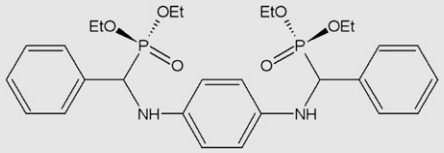
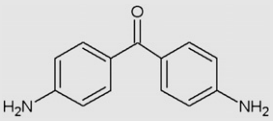
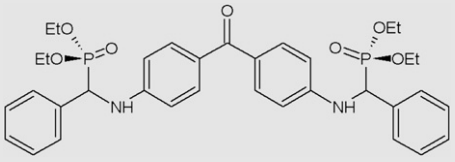
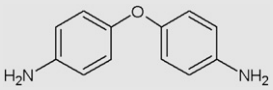
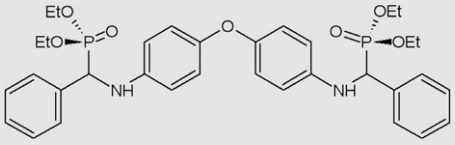
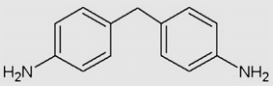
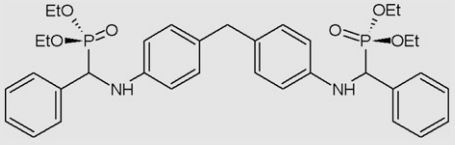
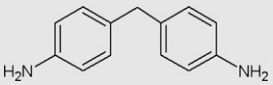
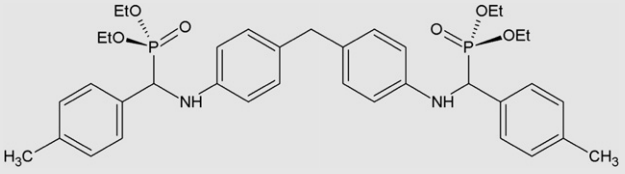
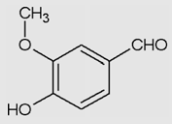
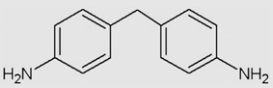
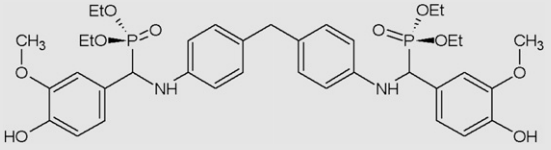
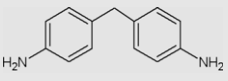
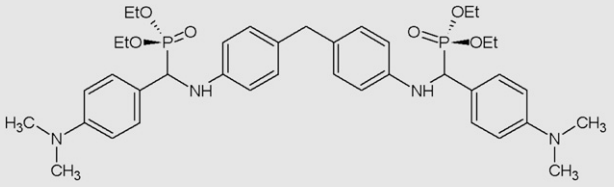
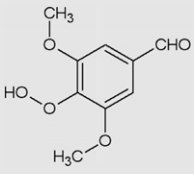
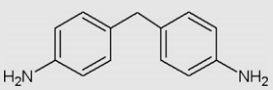
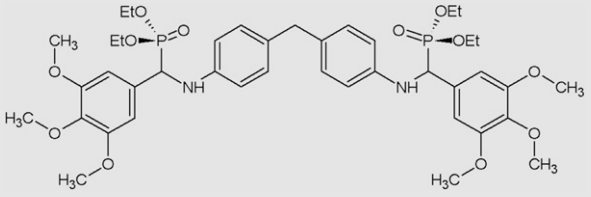
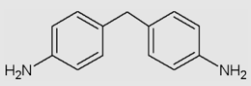
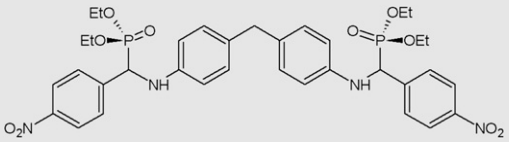
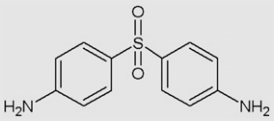
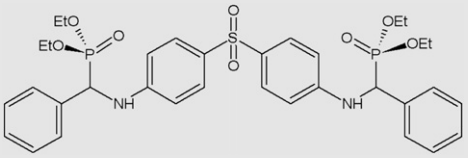
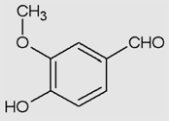
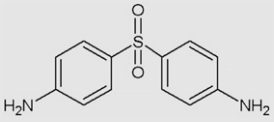
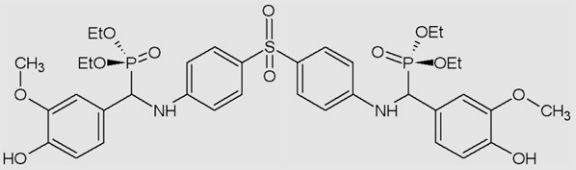
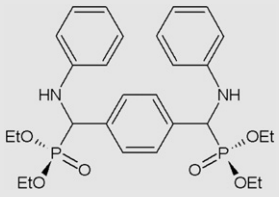
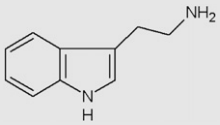
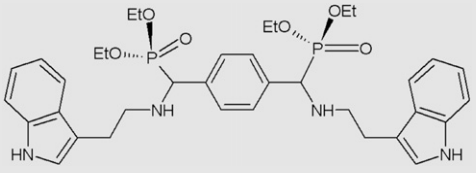
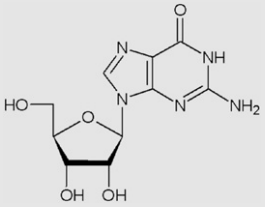
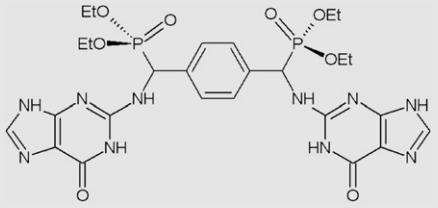
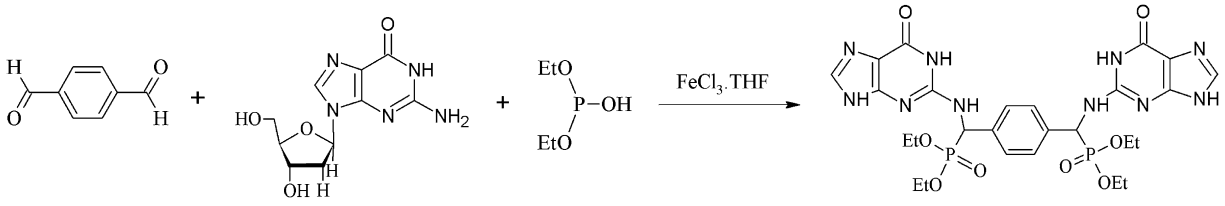
Entry	Aldehyde	Amine	Bis(α-aminophosphonate)	Time (h)	Yield (%)
2a	PhCHO			0.75	96
2b	PhCHO			1	93
2c	PhCHO			2	90
2d	PhCHO			1	92
2e	4-$CH_3C_6H_4CHO$			1	95
2f				1	94
2g	4-$(CH_3)_2NPhCHO$			1	95
2h				1.5	92

Table 3 (*continued*)

Entry	Aldehyde	Amine	Bis(α-aminophosphonate)	Time (h)	Yield (%)
2i	4-$NO_2C_6H_4CHO$			1.5	90
2j	PhCHO			1	93
2k				0.5	82
2l	CHOPhCHO	PhNH		0.85	88
2m	CHOPhCHO			3	68
2n	CHOPhCHO			12	53

5.2. Biological assay

The antitumor activity of the synthesized compounds was measured by MTT method. Three different cell lines JURKAT (T-cell lymphoma), RAJI (Burkit's lymphoma) and MCF-7 (breast cancer) were selected to cover different tumor lines and were purchased from Pasteur Institute of Iran. The Media RPMI 1640 were used and 10% fetal calf serum was added to the media. Compounds **2b**, **2c**, **2d**, **2f**, **2g**, **2h**, **2i**, **2k**, **2l**, **2m**, **2n** were selected to be evaluated by *in vitro* cytotoxicity test.



Scheme 2. Formation of bis(α-aminophosphonate) starting from guanosine.

Table 4
Maximum percentage of inhibition for compound tested at 100 μM, comparing to Final Docking Energy.

Entry	Inhibition (%) of cell lines			FDE[a] (kcal/mol)
	Jurkat	MCF-7	RAJI	
2b	15.75	10.19	0[b]	−12
2c	6.84	0	0	−11.2
2d	27.98	13.95	6.41	−12.2
2f	40.11	29.15	56.18	−10.5
2g	17.8	12.7	0.78	−10.2
2h	20.05	3.5	0	−8.6
2i	10.66	12.16	0	−10.1
2k	15.55	16.63	0	−11.9
2l	36.79	25.4	27.23	−12.15
2m	68.39	54.2	64.78	−15.4
2n	0	12.7	64.78	−10.5
Doxorubicin	82.28	65.47	66.66	−17.2

[a] FDE: Final Docking Energy.
[b] The score 0 shows no inhibition of growth or stimulation of growth.

The MTT studies showed that the most cytotoxic compound was **2m** which has an indole moiety in its structure, with $IC_{50} = 24.3$ μM for JURKAT ($r^2 = 0.982$), $IC_{50} = 45.2$ μM for RAJI ($r^2 = 0.997$) and $IC_{50} = 67.5$ μM for MCF-7 ($r^2 = 0.999$). Compound **2f** showed $IC_{50} = 58.6$ μM for RAJI ($r^2 = 0.967$). All other tested compounds showed $IC_{50} > 100$ μM. The maximum inhibition percentage of the compounds at 100 μM concentration is presented in Table 4.

6. Conclusion

Bis-α-aminophosphonates are valuable compounds to be investigated as bioactive molecules and pharmacological agents. The amine and phosphonate substitutions can interact with enzymes, DNA and receptors to start a pharmacological effect. The synthesis of bis(α-aminophosphonates) is hardly reported in literature.

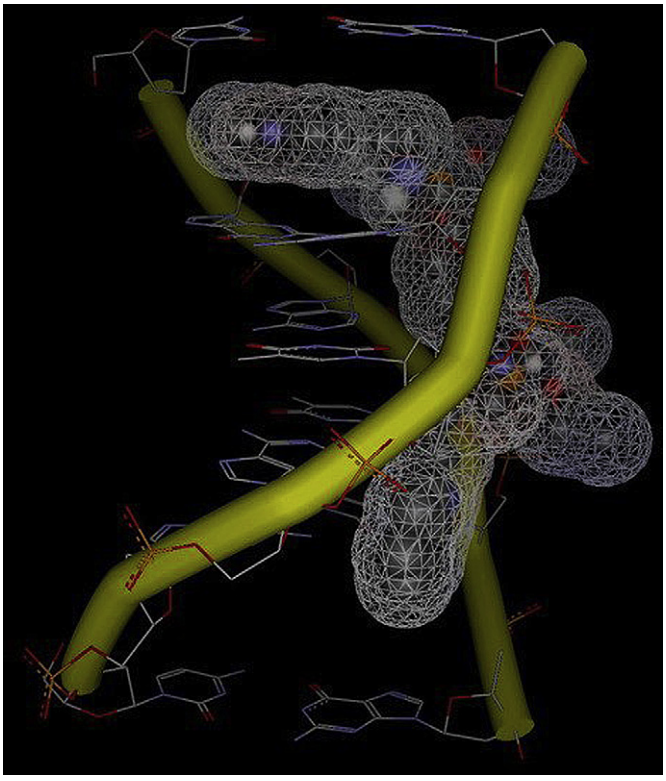


Fig. 1. Compounds **2m** can intercalate into DNA double strand so that one of the indole ring makes a distance in sequential bases.

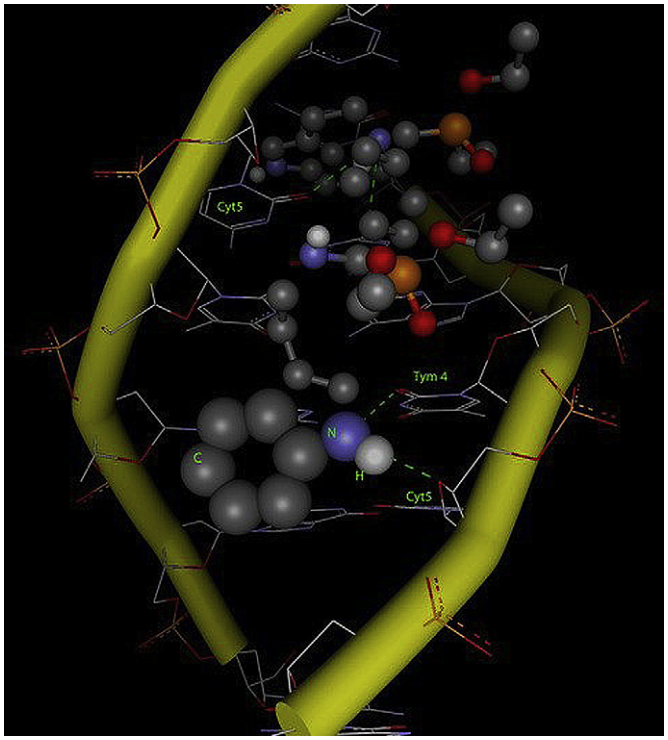


Fig. 2. The hydrogen bonding of O_4 of thymidine 4 (Tym_4) and $O_{2'}$ of cytosine 5 (Cyt_5) of DNA with the indole ring of compound **2m**. The indole ring is scaled up to clarify the picture. The yellow tubes show the backbone of DNA double strands. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In this study, the non-hygroscopic and easy handling solution of $FeCl_3$ in THF has been introduced as a highly efficient bench top catalyst for one-pot synthesis of α-aminophosphonates in excellent yields *via* a three-component coupling reaction of aldehydes, amines, and diethylphosphite. We have also applied this method for the preparation of biologically active bis(α-aminophosphonates) in excellent yields.

The biological assays showed that indole containing bis(α-aminophosphonates) had a high to moderate cytotoxic activity. Although the FDE for the most cytotoxic compound **2m** was of the most negative value, there is no correlation between FDE and cytotoxicity.

7. Experimental

All solvents and reagents were purchased from Sigma or Merck Chemical Companies. The products were purified by column chromatography techniques. NMR spectra were recorded on a Brucker Avance DPX 500 MHZ and 250 MHZ instrument. FT-IR spectroscopy was performed using a Shimadzu 8100.

*7.1. General procedure to synthesis of tetraethyl[4,4′-methylene bis(4,1-phenylene) bis(azanediyl)] bis(phenylmethylene) diphosphonate (**1a**)*

To a mixture of aldehyde (2 mmol), diamine (1 mmol), and diethylphosphite (2.2 mmol) was added $FeCl_3$·THF (2.0 mL, 5.0 mol%) and stirred at 60 °C for the appropriate reaction time. After completion of the reaction (TLC), EtOAc (10 mL) was added to

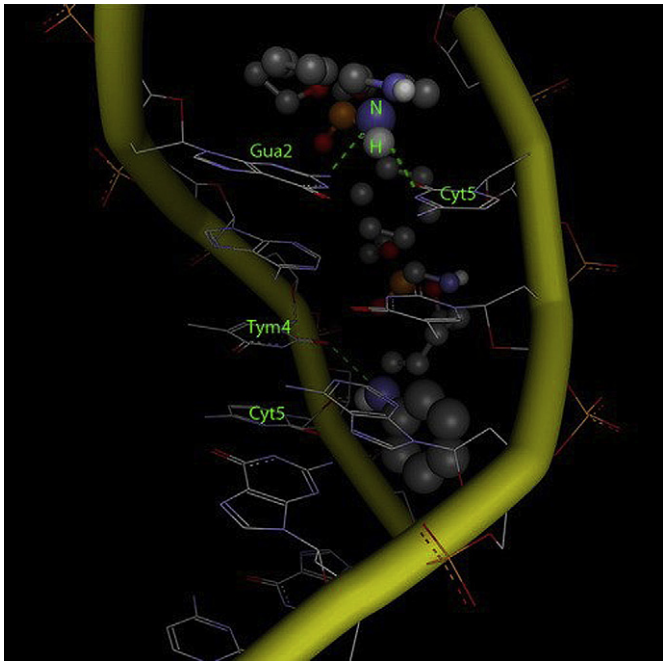


Fig. 3. The hydrogen bonding of N_2 of guanine 2 (Gua_2) and O_2 of cytosine 5 (Cyt_5, upper) of DNA with the NH of compound **2m**. The yellow tubes show the backbone of DNA double strands. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the mixture. The mixture was washed with H_2O (10 mL). The organic phase was separated and dried over anhydrous Na_2SO_4. The solvent was evaporated in vacuo and the resulting crude material was purified by chromatography on a short column of silica gel (EtOAc:petroleum ether, 1:3) and then recrystallized from petroleum benzine/dichloromethane (4:1) to afford the pure bis(α-aminophosphonates). The procedure for the preparation of compounds **2l**, **2m** and **2n** is similar to the above protocol with the ratio of dialdehyde (1.0 mmol)/amine (2.0 mmol)/diethyl phosphate (2.2 mmol)/$FeCl_3 \cdot THF$ (2.0 mL, 5.0 mol%) for the appropriate reaction times.

*7.1.1. Diethylmethyl(phenyl) amino-phenylmethylphosphonate (**1i**)*

Elemental analysis for $C_{18}H_{24}NO_3P$ requires C: 64.85, H: 7.26%, found: C: 64.78%; H: 7.24%; ^{1}H NMR (250 MHz, $CDCl_3$, TMS): 7.5 (d, 2H, $J = 6.3$ Hz, C_6H_5), 7.30–7.20 (m, 5H, C_6H_5), 6.87 (d, 2H, $J = 8.1$ Hz, C_6H_5), 6.77 (t, 1H, $J = 7.1$ Hz, C_6H_5), 5.33 (1H, d, $^1J_{PH} = 24.8$ Hz, CH), 4.24–3.92 (m, 4H, $C\underline{H}_2CH_3$), 2.94 (s, 3H, $\underline{CH}_3$), 1.22–1.16 (m, 6H, $CH_2C\underline{H}_3$) ppm; ^{13}C NMR (62.9 MHz, $CDCl_3$, TMS): 150.2 (d, $^3J_{PC} = 7.3$ Hz), 134.4, 130.2, 129.6, 129.2, 128.9, 128.8, 128.5, 127.9, 118.0, 113.4, 63.1 (d, $^2J_{CP} = 6.4$ Hz), 62.1 (d, $^3J_{PC} = 7.1$ Hz), 61.8 (d, $^1J_{CP} = 159.8$ Hz), 16.5 (d, $^3J_{PC} = 5.5$ Hz), 16.3 (d, $^3J_{PC} = 5.7$ Hz) ppm; IR (KBr): 3294, 2970, 1612, 1242, 1027 cm^{-1}.

*7.1.2. Tetraethyl (1,4-phenylene bis(azanediyl)) bis(phenylmethylene) diphosphonate (**2a**)*

Elemental analysis for $C_{28}H_{38}N_2O_6P_2$ requires C: 59.99%, H: 6.83%, found: C: 60.02%; H: 6.79%; ^{1}H NMR ($CDCl_3$, TMS): 7.47–7.39 (m, 4H, C_6H_5), 7.31–7.22 (m, 6H, C_6H_5), 6.41 (s, 4H, C_6H_4), 4.65 (b, 2H, NH), 4.6 (2H, d, $^1J_{PH} = 24$ Hz, CH), 4.12–4.05 (m, 4H, $C\underline{H}_2CH_3$), 3.92–3.3.85 (m, 2H, $C\underline{H}_2CH_3$), 3.70–3.63 (m, 2H, $C\underline{H}_2CH_3$), 1.24 (t, 6H, $J = 7.1$ Hz, $CH_2C\underline{H}_3$), 1.08 (t, 6H, $J = 7.1$ Hz, $CH_2C\underline{H}_3$) ppm; ^{13}C NMR ($CDCl_3$, TMS): 139.1 (d, $^3J_{PC} = 15.9$ Hz), 136.1, 130.0, 127.8, 127.7, 115.4, 63.2 (d, $^2J_{PC} = 7.5$ Hz), 63.1 (d, $^2J_{PC} = 7.2$ Hz), 57.3 (d, $J_{CP} = 150.3$ Hz), 16.4 (d, $^3J_{PC} = 5.8$ Hz), 16.1 (d, $^3J_{PC} = 5.8$ Hz) ppm; IR (KBr): 3294, 2970, 1612, 1242, 1027 cm^{-1}.

*7.1.3. Tetraethyl[4,4′-carbonyl bis(4,1-phenylene) bis(azanediyl)] bis(phenylmethylene) diphosphonate (**2b**)*

M.p. = 175–176 °C. Elemental analysis for $C_{37}H_{48}N_2O_{10}P_2$ requires C: 6.37%, H: 63.25%, found: C: 62.77%; H: 6.34%; ^{1}H NMR ($CDCl_3$, TMS, 250 MHz): 7.56 (d, 4H, $J = 8.7$ Hz, Ar-H), 7.29–7.47 (d, 4H, $J = 8.7$ Hz, Ar-H), 6.57 (m, 10H, Ar-H), 5.51 (b, 2H, NH), 4.86 (d, 2H, $^2J_{PH} = 24.2$ Hz, CHP), 4.07–4.15 (m, 4H, $C\underline{H}_2CH3$), 3.90–3.94 (m, 2H, $C\underline{H}_2CH3$), 3.62–3.69 (m, 2H, $C\underline{H}_2CH3$), 1.10 (t, 6H, $J = 7$ Hz, CH_3), 1.29 (t, 6H, $J = 7$ Hz, CH_3) ppm. ^{13}C NMR ($CDCl_3$, TMS, 62.9 MHz): 193.81, 149.62, 149.40, 135.25, 128.80, 128.76, 127.82, 127.73, 112.52, 63.30 (d, $^2J_{PC} = 27.2$ Hz), 56.78, 54.39 ($J_{CP} = 149.3$ Hz), 16.22 (d, $^3J_{PC} = 5.7$ Hz), 16.13 (d, $^3J_{PC} = 5.7$ Hz) ppm; IR (KBr): 3278.8, 2973.9, 1612.4, 1596.2, 1527, 1234.3, 1029.8 cm^{-1}.

*7.1.4. Tetraethyl[4,4′-oxy bis(4,1-phenylene) bis(azanediyl)] bis(phenylmethylene) diphosphonate (**2c**)*

M.p. = 115–116 °C. Elemental analysis for $C_{34}H_{42}N_2O_7P_2$ requires C: 62.57%, H: 6.49%, found: C: 62.48%; H: 6.44%; ^{1}H NMR ($CDCl_3$, TMS, 250 MHz): 7.47–7.43 (m, 4H, C_6H_5), 7.30–7.19 (m, 6H, C_6H_5), 6.65 (4H, d, $J_{CH} = 8.9$ Hz, C_6H_4), 6.50 (4H, d, $J_{CH} = 8.9$ Hz, C_6H_4), 4.90 (b, 2H, NH), 4.69 (2H, d, $^1J_{PH} = 24$ Hz, CH), 4.13–4.06 (m, 4H, $C\underline{H}_2CH_3$), 3.92–3.85 (m, 2H, $C\underline{H}_2CH_3$), 3.66–3.63 (m, 2H, $C\underline{H}_2CH_3$), 1.24 (t, 6H, $J = 6.88$ Hz, $CH_2C\underline{H}_3$), 1.07 (t, 6H, $J = 6.88$ Hz, $CH_2C\underline{H}_3$) ppm; ^{13}C NMR ($CDCl_3$, TMS, 62.9 MHz): 150.2 (d, $^3J_{PC} = 16.6$), 142.1, 141.9, 136.0 (d, $^2J_{PC} = 2.3$), 128.4, 127.3, 119.2, 116.3, 63.2 (d, $^2J_{PC} = 6.9$), 63.1 (d, $^2J_{PC} = 6.9$), 56.5 (d, $J_{CP} = 151.0$ Hz), 16.4 (d, $^3J_{PC} = 5.7$), 16.1 (d, $^3J_{PC} = 5.7$) ppm; IR (KBr): 3294, 2985, 1604, 1496, 1226, 1026 cm^{-1}.

*7.1.5. Tetraethyl[4,4′-methylene bis(4,1-phenylene) bis(azanediyl)] bis(phenylmethylene) diphosphonate (**2d**)*

M.p. = 151–152 °C. Elemental analysis for $C_{35}H_{44}N_2O_6P_2$ requires C: 64.61%, H: 6.82%, found: C: 64.51%; H: 6.80%; ^{1}H NMR ($CDCl_3$, TMS, 250 MHz): 7.46–7.43 (4H, m, C_6H_5), 7.31–7.20 (m, 6H, C_6H_5), 6.83 (4H, d, $J_{CH} = 8.3$ Hz, C_6H_4), 6.48 (4H, d, $J_{CH} = 8.3$ Hz, C_6H_4), 4.76 (b, 2H, NH), 4.71 (2H, d, $^1J_{PH} = 24.2$ Hz, CH), 4.13–4.04 (m, 4H, $C\underline{H}_2CH_3$), 3.92–3.85 (m, 2H, $C\underline{H}_2CH_3$), 3.66–3.61 (m, 2H, $C\underline{H}_2CH_3$), 3.62 (2H, s, CH_2), 1.26 (t, 6H, $J = 6.9$ Hz, $CH_2C\underline{H}_3$), 1.07 (t, 6H, $J = 6.9$ Hz, $CH_2C\underline{H}_3$) ppm; ^{13}C NMR ($CDCl_3$, TMS, 62.9 MHz): 144.4 (d, $^3J_{PC} = 15.1$), 136.1, 131.2, 128.9, 128.5, 128.2, 113.9, 63.23 (d, $^2J_{PC} = 6.9$), 63.2 (d, $^2J_{PC} = 7.0$), 56.2 (d, $J_{CP} = 150.3$ Hz), 40.1, 16.4 (d, $^3J_{PC} = 6.3$), 16.2 (d, $^3J_{PC} = 5.8$) ppm; ^{31}P NMR (DMSO, TMS, 200 MHz): 23.46 ppm; IR (KBr): 3298, 2981, 1612, 1517, 1242, 1027 cm^{-1}.

*7.1.6. Tetraethyl[4,4′-methylene bis(4,1-phenylene) bis(azanediyl)] bis(*p*-tolylmethylene)diphosphonate (**2e**)*

Elemental analysis for $C_{37}H_{48}N_2O_6P_2$ requires C: 65.47%, H: 7.13%, found: C: 65.42%; H: 7.11%; ^{1}H NMR ($CDCl_3$, TMS): 7.33 (d, 4H, $J_{CH} = 7.9$ Hz, *p*-Me-C_6H_4), 7.10 (d, 4H, $J_{CH} = 7.9$ Hz, *p*-Me-C_6H_4), 6.84 (4H, d, $J_{CH} = 8.4$ Hz, C_6H_4), 6.48 (4H, d, $J_{CH} = 8.4$ Hz, C_6H_4), 4.67 (b, 2H, NH), 4.67 (2H, d, $^1J_{PH} = 24$ Hz, CH), 4.13–4.05 (m, 4H, $C\underline{H}_2CH_3$), 3.95–3.88 (m, 2H, $C\underline{H}_2CH_3$), 3.69–3.63 (m, 2H, $C\underline{H}_2CH_3$), 3.63 (s, 2H, CH_2), 2.29 (s, 3H, CH_3), 1.26 (t, 6H, $J = 6.88$ Hz, $CH_2C\underline{H}_3$), 1.11 (t, 6H, $J = 6.88$ Hz, $CH_2C\underline{H}_3$) ppm; ^{13}C NMR ($CDCl_3$, TMS): 144.4 (d, $^3J_{PC} = 15.2$), 137.5, 132.8, 131.6, 129.3, 127.7, 113.9, 63.24 (d, $^2J_{PC} = 7.0$), 63.2 (d, $^2J_{PC} = 7.0$), 55.9 (d, $J_{CP} = 151.2$ Hz), 40.0, 21.0, 16.2 (d, $^3J_{PC} = 5.8$), 16.4 (d, $^3J_{PC} = 5.8$) ppm; IR: 3294, 2980, 1612, 1517, 1242, 1027 cm^{-1}.

*7.1.7. Tetraethyl[4,4′-methylene bis(4,1-phenylene) bis(azanediyl)]bis[(3-hydroxy-4-methoxyphenyl)-methylene]diphosphonate (**2f**)*

M.p. = 158–159 °C. Elemental analysis for $C_{37}H_{48}N_2O_{10}P_2$ requires C: 59.83%, H: 6.51%, found: C: 59.69%; H: 6.38%; ^{1}H NMR

($CDCl_3$, TMS, 250 MHz): 6.97–6.86 (m, 10H, Ar-H + 1H, OH), 6.51–6.47 (d, 4H, J_{CH} = 8.3 Hz, C_6H_4 + 1H, OH), 4.61 (b, 2H, NH), 4.61 (2H, d, $^2J_{PH}$ = 23.7 Hz, CH), 4.13–4.08 (m, 4H, $C\underline{H}_2CH_3$), 3.95–3.89 (m, 2H, $C\underline{H}_2CH_3$), 3.84 (s, 6H, OCH_3), 3.70–3.65 (m, 2H, $C\underline{H}_2CH_3$), 3.66 (s, 2H, CH_2), 1.27 (t, 6H, J = 6.88 Hz, $CH_2C\underline{H}_3$), 1.13 (t, 6H, J = 6.88 Hz, $CH_2C\underline{H}_3$) ppm; ^{13}C NMR ($CDCl_3$, TMS, 62.9 MHz): 146.9, 146.2, 144.5 (d, J_{CP} = 150.9 Hz), 131.5, 129.3, 128.5, 119.2 (d, $^2J_{PC}$ = 6.2), 114.6, 113.9, 111.1, 63.25 (d, $^2J_{PC}$ = 6.6), 63.23 (d, $^2J_{PC}$ = 6.7), 55.7, 55.6 (d, J_{CP} = 153.0 Hz), 40.0, 16.3 (d, $^3J_{PC}$ = 5.9), 16.1 (d, $^3J_{PC}$ = 5.7) ppm; IR (KBr): 3297, 3128, 2979, 1608, 1505, 1234, 1147, 1030 cm^{-1}.

7.1.8. Tetraethyl[4,4′-methylene bis(4,1-phenylene) bis-(azanediyl)] bis[(4-(dimethylamino)phenyl)methylene]diphosphonate(**2g**)

M.p. = 150–151 °C. Elemental analysis for $C_{37}H_{48}N_2O_{10}P_2$ requires C: 63.57%, H: 7.39%, found: C: 63.09%; H: 7.35%; ^{1}H NMR ($CDCl_3$, TMS, 250 MHz): 7.27 (d, 4H, J = 8.7 Hz, Ar-H), 6.85 (d, 4H, J = 8.4 Hz, Ar-H), 6.68 (d, 4H, J = 8.7 Hz, Ar-H), 6.49 (d, 4H, J = 8.4 Hz, Ar-H), 4.52–4.63 (b, 2H, NH), 4.60 (d, 2H, $^2J_{PH}$ = 25 Hz, CHP), 4.03–4.12 (m, 4H, $C\underline{H}_2CH3$), 3.87–3.94 (m, 2H, $C\underline{H}_2CH3$), 3.63–3.68 (m, 2H, $C\underline{H}_2CH3$), 3.65 (s, 2H, CH_2), 2.91 (s, 12H, NCH_3), 1.26 (t, 6H, J = 7 Hz, $CH_2C\underline{H}_3$), 1.12 (t, 6H, J = 7 Hz, $CH_2C\underline{H}_3$); ^{13}C NMR ($CDCl_3$, TMS, 62.9 MHz): 131.4, 129.3, 128.6, 128.5, 123.2, 112.5, 112.5, 113.9, 63.0 (d, $^2J_{P-C}$ = 3.75 Hz), 55.5 (d, J_{CP} = 152 Hz), 40.5, 40.0, 16.5 (d, $^3J_{PC}$ = 5.75 Hz), 16.3 (d, $^3J_{PC}$ = 5.75 Hz) ppm. IR (KBr): 3263, 2987, 1613, 1516, 1516, 1227, 1329, 1029 cm^{-1}.

7.1.9. Tetraethyl(4,4′-methylene bis(4,1-phenylene)) bis(azanediyl) bis((3,4,5-trimethoxyphenyl)methylene)diphosphonate (**2h**)

M.p. = 72–73 °C. Elemental analysis for $C_{37}H_{48}N_2O_{10}P_2$ requires C: 59.13%, H: 7.02%, found: C: 58.68%; H: 6.99%; ^{1}H NMR ($CDCl_3$, TMS, 250 MHz): 6.904 (d, 4H, J = 8.25, Ar-H), 6.714 (s, 4H, Ar-H), 6.527 (d, 4H, J = 8.25 Hz, Ar-H), 4.598 (d, 2H, $^2J_{PH}$ = 24.1 Hz, CHP), 4.053–4.135 (m, 4H, O**CH_2**CH_3), 3.915–3.984 (m, 2H, $C\underline{H}_2CH_3$), 3.687–3.765 (m, 2H, $C\underline{H}_2CH_3$), 3.826 (s, 18H, OCH_3), 3.704 (s, 2H, CH_2), 1.275 (t, 6H, J = 7 Hz, CH_3), 1.141 (t, 6H, J = 7 Hz, CH_3) ppm. ^{13}C NMR ($CDCl_3$, TMS, 62.9 MHz): 153.2, 144.7, 131.8, 131.7, 129.4, 113.9, 104.7, 104.7, 63.2 (d, $^2J_{PC}$ = 4.4 Hz, $C\underline{H}_2CH$), 56.6 (d, J_{CP} = 187.2 Hz), 56.1, 40.1, 16.4 (d, $^3J_{PC}$ = 5.8 Hz), 16.2 (d, $^3J_{PC}$ = 5.8 Hz) ppm; ^{31}P NMR (DMSO, TMS, 200 MHz): 23.46 ppm; IR (KBr): 3263.5, 2973.2, 1594.2, 1477.4, 1527, 1228.1, 1234.4, 1029.8 cm^{-1}.

7.1.10. Tetraethyl[4,4′-methylene bis(4,1-phenylene) bis(azanediyl]) bis[(4-nitrophenyl)methylene]diphosphonate (**2i**)

M.p. = 184–185 °C. Elemental analysis for $C_{35}H_{42}N_4O_{10}P_2$ requires C: 56.76%, H: 5.72%, found: C: 56.71%; H: 5.70%; ^{1}H NMR ($CDCl_3$, TMS, 250 MHz): 8.18 (d, 4H, J_{CH} = 8.2 Hz, *p*-NO_2–C_6H_4), 7.64 (d, 4H, J_{CH} = 8.18 Hz, *p*-NO_2–C_6H_4), 6.86 (4H, d, J_{CH} = 8.4 Hz, C_6H_4), 6.42 (4H, d, J_{CH} = 8.4 Hz, C_6H_4), 4.80 (2H, d, $^2J_{PH}$ = 25.3 Hz, CH), 4.75 (b, 2H, NH), 4.15–3.85 (m, 8H, $C\underline{H}_2CH_3$), 3.65 (s, 2H, CH_2), 1.28 (t, 6H, J = 6.88 Hz, $CH_2C\underline{H}_3$), 1.17 (t, 6H, J = 6.88 Hz, $CH_2C\underline{H}_3$) ppm; ^{13}C NMR ($CDCl_3$, TMS, 62.9 MHz): 147.5, 144.1 (d, $^3J_{PC}$ = 3.1), 143.7 (d, $^2J_{PC}$ = 14.6), 132.2, 131.6, 129.6, 128.7, 128.6, 123.7, 113.9, 63.7 (d, $^2J_{PC}$ = 7.0), 63.4 (d, $^2J_{PC}$ = 6.8), 56.1 (d, J_{CP} = 148.2 Hz), 40.0, 21.0, 16.4 (d, $^3J_{PC}$ = 5.7), 16.2 (d, $^3J_{PC}$ = 5.7) ppm; IR (KBr): 3290, 2979, 1610, 1514, 1344, 1234, 1029 cm^{-1}.

7.1.11. Tetraethyl[4,4′-sulfonyl bis(4,1-phenylene) bis(azanediyl)] bis(phenylmethylene)diphosphonate (**2j**)

Elemental analysis for $C_{34}H_{42}N_2O_8P_2S$ requires C: 58.28%, H: 6.04%, found: C: 58.23%; H: 6.01%; ^{1}H NMR ($CDCl_3$, TMS): 7.54 (4H, d, J_{CH} = 7.8 Hz, C_6H_4), 7.41–7.26 (m, 10H, C_6H_5), 6.56 (4H, d, J_{CH} = 7.8 Hz, C_6H_4), 5.68 (b, 2H, NH), 4.69 (2H, d, $^1J_{PH}$ = 24 Hz, CH), 4.13–4.04 (m, 4H, $C\underline{H}_2CH_3$), 3.92–3.84 (m, 2H, $C\underline{H}_2CH_3$), 3.63–3.55 (m, 2H, $C\underline{H}_2CH_3$), 1.24 (t, 6H, J = 6.88 Hz, $CH_2C\underline{H}_3$), 1.07 (t, 6H, J = 6.88 Hz, $CH_2C\underline{H}_3$) ppm; ^{13}C NMR ($CDCl_3$, TMS): 150.0 (d, $^3J_{PC}$ = 13.7), 134.9, 130.9, 128.9, 128.7, 128.2, 127.8, 113.0, 63.6 (d, $^2J_{PC}$ = 6.7), 63.3 (d, $^2J_{PC}$ = 6.7), 56.6 (d, J_{CP} = 151.5 Hz), 16.3 (d, $^3J_{PC}$ = 5.6), 16.1 (d, $^3J_{PC}$ = 5.6) ppm; ^{31}P NMR (DMSO, TMS, 200 MHz): 22.90 ppm; IR: 3248, 2978, 1594.3, 1506.7, 1287, 1237, 1100, 1029.8 cm^{-1}.

7.1.12. Tetraethyl[4,4′-sulfonyl bis(4,1-phenylene) bis(azanediyl)] bis((4-hydroxy-3-methoxyphenyl)methylene)diphosphonate (**2k**)

M.p. = 158–159 °C. Elemental analysis for $C_{34}H_{42}N_2O_8P_2S$ requires C: 54.54%, H: 5.85%, found: C: 54.12%; H: 5.83%; ^{1}H NMR ($CDCl_3$, TMS, 250 MHz): 7.575 (d, 4H, J = 8.7 Hz, Ar-H), 6.824–6.905 (m, 6H, Ar-H), 6.572 (d, 4H, J = 8.7 Hz, Ar-H), 5.332 (b, 2H, NH), 4.8656 (d, J_{PH} = 23.8 Hz, 2H, CHP), 4.033–4.129 (m, 4H, $C\underline{H}_2CH3$), 3.9069–3.9474 (m, 2H, $C\underline{H}_2CH3$), 3.621–3.697 (m, 2H, $C\underline{H}_2CH3$), 1.2902 (t, 6H, J = 7 Hz, $C\underline{H}_3$), 1.1047 (t, 6H, J = 7 Hz, CH_3) ppm. ^{13}C NMR ($CDCl_3$, TMS, 62.9 MHz): 147.7, 131.0, 129.0, 126.2, 120.9, 114.6, 113.0, 110.0, 63.414 (d, $^2J_{PC}$ = 6.9 Hz), 55.182 (d, J_{CP} = 151.75 Hz), 55.9, 16.478 (d, $^3J_{PC}$ = 5.1 Hz), 16.213 (d, $^3J_{PC}$ = 5.1 Hz) ppm; IR (KBr): 3248, 2978, 1594, 1506, 1287, 1237, 1100, 1029 cm^{-1}.

7.1.13. Tetraethyl-1,4-phenylenebis[(phenylamino) methylene]diphosphonate (**2l**)

M.p. = 159–160 °C. Elemental analysis for $C_{28}H_{38}N_2O_6P_2$ requires C: 59.99%, H: 6.83%, found: C: 59.63%; H: 6.80%; ^{1}H NMR ($CDCl_3$, TMS, 250 MHz): 7.40 (s, 4H, C_6H_4), 7.22–7.15 (m, 4H, C_6H_5), 6.87–6.75 (m, 2H, C_6H_5), 6.70–6.65 (m, 4H, C_6H_5), 4.79 (b, 2H, NH), 4.78 (d, J = 23.3 Hz, 2H, CH), 4.18–3.88 (m, 4H, $C\underline{H}_2CH_3$), 3.91–3.76 (m, 2H, $C\underline{H}_2CH_3$), 3.68–3.55 (m, 2H, $C\underline{H}_2CH_3$), 1.04 (t, J = 7.0 Hz, 6H, $CH_2C\underline{H}_3$), 0.93 (t, J = 7.0 Hz, 6H, $CH_2C\underline{H}_3$), ^{13}C NMR ($CDCl_3$, TMS, 62.9 MHz): 135.8, 129.1, 128.2, 118.4, 113.9, 63.3, 55.8 (d, J_{PC} = 150.1 Hz), 16.4 ppm; IR (KBr): 3294, 2978, 1605, 1497, 1242, 1027 cm^{-1}.

7.1.14. Tetraethyl-1,4-phenylene bis((2-(1H-indolyl) ethylamino)methylene)diphosphonate (**2m**)

Yellow oily liquid. Elemental analysis for $C_{28}H_{38}N_2O_6P_2$ requires C: 62.24%, H: 6.96%, found: C: 61.77%; H: 6.93%; ^{1}H NMR ($CDCl_3$, TMS, 500 MHz): 8.57 (d, J_{NH} = 7.5 Hz, 2H, Ar-NH), 6.79–7.54 (m, 14H, Ar-NH), 4.32 (dd, 2H, J = 19.5, J = 20.1 Hz, CHP), 4.01–4.10 (m, 4H, $C\underline{H}_2CH3$), 3.92–3.98 (m, 2H, $C\underline{H}_2CH3$), 3.798–3.834 (m, 2H, $C\underline{H}_2CH3$), 2.88–2.94 (m, 8H, $C\underline{H}_2C\underline{H}_2N$), 2.085 (b, 2H, CH_2NH), 1.26–1.20 (m, 6H, CH_3), 1.1 (m, 6H, $C\underline{H}_3$). ^{13}C NMR ($CDCl_3$, TMS, 125 MHz): 136.8, 128.9, 127.8, 127.5, 122.5, 122.116, 119.4, 119.0, 113.5, 111.6, 63.3 (d, J_{PC} = 6.75 Hz), 61.1 (d, J_{CP} = 151.2 Hz) 48.479, 25.8, 16.8 ppm; ^{31}P NMR (DMSO, TMS, 200 MHz): 24.02 ppm; IR (KBr): 3118.4, 2973.2, 1224.7, 1018.3.

7.1.15. Tetraethyl-1,4-phenylene bis[(6-oxo-6,7-dihydro-1H-purin-2yl-amino)methylene]diphosphonite (**2n**)

M.p. = 73–74 °C. Elemental analysis for $C_{26}H_{34}N_{10}O_8P_2$ requires C: 46.16%, H: 5.07%, found: C: 45.81%, H: 5.05%; ^{1}H NMR ($CDCl_3$, TMS, 500 MHz): 9.98 (s, 2H, NH), 7.84 (s, 2H, NH), 7.83 (s, 2H), 7.63 (d, 4H, J = 6.7 Hz, C_6H_4), 5.45 (b, 2H, NH), 5.10 (d, 2H, J_{PH} = 12.7 Hz, CH), 4.08–4.00 (m, 8H, $C\underline{H}_2CH_3$), 1.24–1.17 (m, 12H, $CH_2C\underline{H}_3$) ppm; ^{13}C NMR ($CDCl_3$, TMS, 125 MHz): 192.5, 144.4, 136.2, 129.9, 128.00, 127.9, 70.8 (d, J_{CP} = 157.8 Hz, CH), 64.2 (d, $^2J_{PC}$ = 7.1 Hz), 63.6 (d, $^2J_{PC}$ = 7.6 Hz), 16.8 (d, $^3J_{PC}$ = 4.7 Hz), 16.7 (d, $^3J_{PC}$ = 5.0 Hz) ppm; IR (KBr): 3227, 2973, 1695, 1594, 1232, 1029 cm^{-1}.

Acknowledgement

This work was supported by Shiraz University of Medical Sciences and Shiraz Institute for Cancer Research.

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