1. Introduction

Organophosphorus compounds (OPs), which are a wide class of chemical compounds containing organic moieties usually bonded directly to phosphorus or bonded through a heteroatom, such as sulfur, oxygen or nitrogen, are some of the most common chemicals in the human environment. Because of their unique properties and high biological activity, they have largely been used worldwide in agricultural (pesticides),¹ industrial (production of lubricants, hydraulic fluids, and plastics materials),² medicinal (drugs against osteoporosis, anticancer and antiviral compounds)³,⁴ or veterinary (anthelmintics) applications.⁵ The first potent synthetic organophosphorus poison, tetraethyl pyrophosphate (TEPP), was synthesized by Clermont in 1854. At the beginning of the twentieth century, some very toxic compounds were used in many armed conflicts as chemical weapons, known as chemical warfare agents (CWA). Following the German laboratories discovery of soman, sarin and tabun, the United States and England developed VX production technologies. The book “Chemical Warfare Agents”⁶ discusses the physicochemical properties of chemical warfare agents, their dispersion and fate in the environment, their toxicology and management of their effects on humans, decontamination, and protective equipment. After the Second World War, OPs have been used mainly as pesticides for plants and animals. Furthermore, OPs have practically contributed to the substantial benefits for efficient food production and the fight against many serious diseases, such as malaria, yellow fever, typhus,⁷ or smallpox.⁸

2. Bisphosphonates in the treatment of osteoporosis

Osteoporosis is one of the most serious health problems in the world, and prevention and treatment are of great interest in the European Union, which issued “Report on Osteoporosis in the European Community – Action for Prevention”.⁹ The scale of the problem is alarming. One in three women and one in eight men over the age of 50 years will experience at least one fracture due to osteoporosis in their lifetime. The main criterion for selecting an osteoporosis therapy is its impact on the risk of osteoporotic fracture (femoral neck, spine, wrist). The following pharmacological methods are used:

- hormone replacement therapy;
- specific estrogen receptor modulators (SERMs);
- calcitonin;
- vitamin D3 with active metabolites and calcium;
- fluorine.

Bisphosphonates are currently the most important and effective class of drugs developed for the treatment of metabolic bone disorders associated with increased osteoclast-mediated bone resorption, such as osteoporosis⁹,¹⁰ and Paget’s disease.¹¹,¹² They are effective inhibitors of tumor-induced bone destruction and significantly reduce the incidence of skeletal complications in patients with bone metastases from several forms of cancer, including breast and prostate cancer.¹³ Bisphosphonates have a high affinity for calcium and therefore specifically target bone mineral, where they are internalized by bone-destructing osteoclasts and inhibit their function.¹⁴ Importantly, potential of bisphosphonates has also been identified in areas ranging from parasite-growth inhibition to immunological and cancer therapeutics.³ These compounds primarily affect the function of osteoclasts, but recent preclinical evidence indicates that other neighboring cell types, such as...
macrophages, monocytes and cancer cells, could also be targets for these drugs.\(^7\) Bisphosphonates have been shown to induce tumor cell apoptosis, to modulate cells in the immune system and to inhibit tumor angiogenesis.

Bisphosphonates used in clinical practice are characterized by a P–C–P structure.\(^8\) This structure allows for a wide variety of variations. The first bisphosphonates were synthesized by German chemists and were first used only for a few industrial applications, such as antiscaling agents. It was only in 1968–1969 that H. Fleisch et al. demonstrated that these compounds had biological effects, specifically on calcified tissues.\(^17\)–\(^20\) Replacing the O atom with a CH\(_2\) group in the pyrophosphoric acid structure created new bioactive phosphorus agents and resulted in a major breakthrough in the treatment of bone disease. It is hypothesized that bisphosphonic acid 1 is isotoxic to pyrophosphoric acid 2 but are hydrolytically stable, and if attracted to bone, may block resorption since inorganic pyrophosphate inhibits the formation and dissolution of hydroxyapatite in bone (Fig. 1).

E. Breuer’s research group from the Hebrew University of Jerusalem between 1992 and 2005 had a significant impact on the synthesis and biological evaluation of bisphosphonates. E. Breuer’s research group authored numerous publications and patents concerning the use of bisphosphonates for the treatment of osteoporosis. These researchers were focused on synthesizing novel bifunctional compounds, such as bisacylphosphonates 3,\(^21\) tetrakisphosphonates 4,\(^22\) bisphosphonic acid betaine derivatives 5 (ref. 23) and hydroxyiminophosphonates 6,\(^24\) and examining their effects compared to other clinically used drugs (Fig. 2).

The drugs clodronate 7, tiludronate 8 and etidronate 9 were among the first to be used in the clinic.

Attention has recently been drawn to the derivatives with aminoalkyl side chains for the next generation of bisphosphonates, as found in pamidronic acid 10, alendronic acid 11, olpadronic acid 12, neridronic acid 13, ibandronic acid 14 and risedronic acid 15.

![Fig. 1 Chemical structures of bisphosphonic acid 1 and pyrophosphoric acid 2.](image1)

![Fig. 2 Chemical structures of bisacylphosphonates 3, tetrakisphosphonates 4, bisphosphonic acid betaine derivatives 5 and hydroxyiminophosphonates 6.](image2)

The research field is currently very active, and many new discoveries in bisphosphonate bone-disease therapy have been published.\(^25\) Bisphosphonates are currently in the third generation, which includes incadronic acid 16, minodronic acid 17 and zoledronic acid 18. In addition, several bisphosphonates act as antidepressant 19 and antihypercholesterolemic agents 20 (Fig. 3).\(^26\)–\(^27\)

### 3. Organophosphorus compounds as anticancer drugs

Recent research findings suggest that a number of OPs are used as anticancer drugs or have potential anticancer properties. They are usually used in oncology as alkylating chemotherapeutic agents. These compounds react with DNA, RNA and some enzymes. \(N,N',N''\)-Triethylenethiophosphoramide 21, sold under the trade name thioTEPA, is a compound used as an anticancer chemotherapeutic drug that binds to DNA, cross-links the two strands and prevents cell duplication. \(N,N',N''\)-Triethylenethiophosphoramide, developed in the 1950s, is a trifunctional alkylating agent with a broad spectrum of antitumor activity.\(^28\) This drug is used to treat many diseases, including breast cancer, ovarian cancer, lymphosarcoma, superficial papillary carcinoma of the urinary bladder, and Hodgkin’s disease (Fig. 4).\(^29\)

Several derivatives of \(N,N',N''\)-triethylenethiophosphoramide have been synthesized, and their antitumor activity was evaluated. McCracken and co-workers carried out the synthesis of \(N\)-[bis[1-aziridinyl]phosphoro]carbamate 22.\(^30\) In vivo studies demonstrated that the synthesized drugs had a higher toxicity against cancer cells, and they did not invade other tissues. In 1963, Chernov et al.\(^11\) published the synthesis and biological evaluation of phosphazine 23. Chernov’s research
demonstrated phosphazine’s high activity against transplanted carcinoma in mice, rats, and rabbits. According to these investigations, phosphazine is toxic; however, its toxicity is much lower than thio-phosphamide (thio-TEPA) or dipin (N,N'-bis(diaziridinylphosphonyldyne)piperazine). In 1968, Noell et al. synthesized methylphosphazine (P,N-bis(2-methyl-1-aziridinyl)-N-2-pyrimidinylphosphosphinic amide) which demonstrated excellent activity against both leukemia L1210 and Walker 256 and was more active and less toxic than several clinical drugs, such as thioTEPA and phosphazine. In the 1980s, further structural modifications were tested. Sosnovsky synthesized the nitroxy-labeled analogues of tiamide (TEPA). These studies showed that compounds possess therapeutic indexes 8- to 12-fold higher than those of thio-TEPA and TEPA.

Several of the most important OPs that exhibit anticancer properties are oxazaphosphorines. Even today, 50 years after its introduction, this class of compounds is one of the most widely used cytostatics. The more than 35 000 scientific publications regarding this compound demonstrate the wide interest it has received.

These compounds (Table 1), classified as alkylating agents, are therapeutically inactive prodrugs that must be activated to induce their cytotoxicity. Currently, cyclophosphamide 27 and ifosfamide 29 are used commonly for the treatment of non-Hodgkin lymphomas and a variety of bone and soft tissue sarcomas. Compared to many other anticancer drugs, cyclophosphamide exhibits relatively little non-hematopoietic toxicity.

In 2000, a series of naphthoquinone 31 and benzimidazolequinone 32 phosphorodiamidates were synthesized and studied as potential cytotoxic produgs activated by DT-diaphorase, and an activation process was proposed (Fig. 5). To activate the synthesized produgs, the quinone moiety is reduced to form phosphoramid mustard. All compounds were excellent substrates for human DT-diaphorase. The naphthoquinones 31 showed high toxicity towards both HT-29 and BE human colon cancer cell lines and were 1- to 2-fold more active than the benzimidazolequinone derivatives 32.

In 2008, Jian-Xin Duan et al. synthesized new phosphor-organic compounds with anticancer activity based on 2-nitroimidazole derivatives. These compounds are hypoxia-activated achiral phosphoramidate mustards synthesized based on the DNA cross-linking toxin from the prodrug ifosfamide. Hypoxia-activated phosphoramidates were introduced by Borch and coworkers. The most successful were the 5-nitrothiophene- and 5-nitrofuran-triggered produgs of phosphoramidate toxins. The synthetic methods (Fig. 6) were very straightforward and high yielding. The most promising antitumor agent was TH-302 33, which demonstrated excellent in vivo efficacy and is currently in clinical trials.

In 2003, Jain et al. proposed a new class of 1,2-benzisoxazole phosphorodiamidate compounds. As expected, in vivo studies showed that the compounds 34, 35, and 36 were 3- to 5-fold more active than analogues 37 and 38 (Fig. 7).

Organophosphorus compounds are also used as prospective treatments for hormone-dependent breast cancer. They are included in the list of steroid sulfatase (STS) inhibitors, an enzyme involved in the biosynthesis of estrogen in the mammary glands. The WHO lists estrogen as an important factor in the development of breast cancer. Breast cancer is the

<table>
<thead>
<tr>
<th>Substance</th>
<th>R₁</th>
<th>R₂</th>
<th>R₃</th>
</tr>
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<tbody>
<tr>
<td>Cyclophosphamide 27</td>
<td>CH₃CH₂Cl</td>
<td>H–</td>
<td>H–</td>
</tr>
<tr>
<td>Mafosfamide 28</td>
<td>CH₃CH₂Cl</td>
<td>H–</td>
<td>–O,S–H₂C–CH₂–S–</td>
</tr>
<tr>
<td>Ifosfamide 29</td>
<td>H–</td>
<td>Cl–H₂C–CH₂–</td>
<td>H–</td>
</tr>
<tr>
<td>Trofosfamide 30</td>
<td>CH₃CH₂Cl</td>
<td>Cl–H₂C–CH₂–</td>
<td>H–</td>
</tr>
</tbody>
</table>
most frequently diagnosed cancer in the female population of industrialized countries. Estimates for 2014 show more than 230 000 diagnosed cases of breast cancer and more than 40 000 deaths (according to National Cancer Institute data). Inhibitors based on OPs show potential as new breast cancer therapies because they are structurally similar to the natural steroid sulfatase substrate and have excellent binding affinities to the enzyme active site.42

The initial strategy employed for generating a lead STS inhibitor involved replacement of the sulfate group (OSO₃) on the natural enzyme substrate with surrogates or mimics such as phosphates or thiophosphates. Recently, Demkowicz et al. synthesized new phosphate and thiophosphate esters of tricyclic coumarin 39,34,44 N-alkanoyl tyramine 40,45 biphenyl 41 (ref. 46) and flavone 42 (ref. 47) derivatives as potent STS inhibitors. The most active compound, 4-(2-dodecanoylaminoethyl)-phenyl dimethyl phosphate, demonstrated the greatest inhibitory effect, with IC₅₀ values of 390 nM in enzymatic assay with STS isolated from the human placenta. Although the mechanism of activity is unknown, docking studies conducted to explore the potential interactions between synthesized compounds and the active site of STS suggest a phosphate group transfer to one of the key amino acid residue involved in the enzymatic reaction (FGly75) or methylation of this residue during the inactivation process.

In 2015, the same research group synthesized a series of bicoumarin 43 (ref. 48) and biflavone 44 (ref. 47) thiophosphate derivatives as STS inhibitors. The most active compound, bis-(6-oxo-7,8,9,10-tetrahydro-6H-benzof[c]chromen-3-yl) hydrogen thiophosphate, inhibit STS activity with IC₅₀ values of 860 nM in enzymatic assay with purified STS. Although the mechanism of inhibition also remains unclear, molecular modeling suggests a completely different manner of binding to the active site of STS in comparison to previous organophosphorus inhibitors of STS. Indeed, they can adopt conformations that are able to fill the whole cavity and prevent the substrate’s access to the catalytic amino acid residues.

In 2001, David et al. demonstrated the utility of a new anticancer drug called apomine 45, a per os-active, apoptosis-inducing agent that recently entered clinical trials in cancer patients.49 The clinical trial findings revealed that the drug can selectively inhibit cell proliferation and induce tumor cell apoptosis through the farnesoid X receptor. In vitro assay results showed that 63 and 91% of ovarian cancers were sensitive to apomine at concentrations of 10 and 20 μM, respectively. This compound also inhibits the mevalonate/isoprenoid pathway of cholesterol synthesis and may also prove effective as a skin cancer chemoprevention therapy.50

Another drug used in cancer therapy is combretastatin A-4 phosphate (CA4P) 46,51 Combretastatin A-4 phosphate is a novel microtubule destabilizing drug, a type of vascular-targeting agent designed to damage the vasculature (blood vessels) of cancer tumors and cause central necrosis. It is the first of a series of combretastatin analogs to enter the clinic (Fig. 8).

The structure of CA4P is similar to colchicine 47, and it binds the colchicine-binding site on tubulin and inhibits tubulin polymerization.52 Clinical studies showed that CA4P’s toxicity profile is consistent with a drug that is vascularly active and devoid of traditional cytotoxic side effects.53

The latest achievement in the treatment of cancer is the use of antisense drugs.54–55 Antisense therapy is based on oligonucleotides expected to stop or reduce the expression of selected genes using different approaches based on sequence specific targeting of nucleic acids.56 This new anticancer strategy has been widely used to treat cancers such as colorectal carcinoma, lung cancer, pancreatic carcinoma, malignant glioma or malignant melanoma. Most therapies have not yet produced significant clinical results, and application of this method is the subject of intensive investigations.

4. Organophosphorus metal complexes

Research about the applications of metal complexes in medicine is one of the most integrated areas of science, combining
data regarding structure, properties of metal complexes, and control of the body’s vital processes. The design of new drugs based on metal complexes is an important contribution to the development of more efficient chemotherapy methods. These metal complexes are used in the treatment of many diseases. However, it was not until the early 1960’s that the biological effect of cisplatin was discovered. Primary research by Rosenberg indicated that metal ions were capable of binding to nucleic acids, thereby altering their conformation and biological function. Metal complexes play an important role in many biological processes including cell division and gene expression, as well as processes such as carcinogenicity or toxicity. Among the synthesized compounds, many very important complexes are based on OPs. The literature indicates that most studies consider OPs to have potential anti-cancer aspects. Their activity against many types of cancer is currently the subject of intensive research. Organophosphorus metal complexes include platinum, ruthenium, palladium, gold and copper metal centers.

High in vitro activities of ruthenium complexes against different cancer cell lines suggest that they are the most promising in anticancer therapy and may play a dominant role as antitumor drugs compared to others metal complexes. Among a number of ruthenium complexes, NAMI-A and KP1019 are currently entered into a clinical trials. Although, the mechanism of action for these compounds is not fully understood, recent reports indicate that antiproliferative activity of Ru complexes is strengthened with the interactions with DNA and different cellular proteins. Among the many synthesized ruthenium compounds that exhibit antitumor activity, the arene PTA ruthenium(II) complexes (RAPTA) are of great interest. The RAPTA complexes were found to exhibit pH-dependent DNA damage. Although the cytotoxicity of the new complexes proved to be lower compared to cisplatin, progress has been made in designing new and selective drugs without the harsh side effects of cisplatin.

Efforts to synthesise of ruthenium complexes that exhibit potent anticancer properties led to the discovery of other RAPTA derivatives. Among the synthesized compounds, NAMI-A and KP1019 are currently entered into a clinical trials. Although, the mechanism of action for these compounds is not fully understood, recent reports indicate that antiproliferative activity of Ru complexes is strengthened with the interactions with DNA and different cellular proteins. Among the many synthesized ruthenium compounds that exhibit antitumor activity, the arene PTA ruthenium(II) complexes (RAPTA) are of great interest. The RAPTA complexes were found to exhibit pH-dependent DNA damage. Although the cytotoxicity of the new complexes proved to be lower compared to cisplatin, progress has been made in designing new and selective drugs without the harsh side effects of cisplatin.

5. Phosphorus analogs of amino acids and peptides

Aminophosphinic and aminophosphonic acids are a very important group of chemical compounds, and their synthesis has attracted considerable attention in medicinal chemistry. Although the biological importance of these compounds was discovered in the 1950’s, they still represent a promising class of potential drugs. They are classified as antimetabolites, which
compete with their aminocarboxylic acid analogues in the active sites of enzymes and other cell receptors.\textsuperscript{76–79}

5.1. Aminophosphinic acid derivatives

V. Dive synthesized and evaluated a series of cyclic peptides containing a phosphinic bond as potential zinc bacterial collagenase inhibitors.\textsuperscript{80} Studying collagenases or other proteases helps to better understand the pathology and treatment of human diseases such as rheumatoid arthritis, tissue repair, metastasis, angiogenesis or cirrhosis. Among the synthesized pseudopeptides with different sized cyclic rings, they found two compounds, (cyclo[Gly-Pro-Phe$(\text{PO}_2\text{CH}_2)$-Gly-Pro-Ahx]) and (cyclo[\text{Ala-Pro-Phe}$\psi$(\text{PO}_2\text{CH}_2)$-Gly-Pro-Ahx]), exhibited very potent inhibition activity with $K_i$ values of 120 and 90 nM, respectively. The authors found that the stereochemistry and conformation of the pseudophenylalanine residue determined the potency of these cyclic peptides.

Bartlett and coworkers reported the synthesis and application of phosphonic acid peptide analogues, potent slow-binding inhibitors of aspartic peptidases.\textsuperscript{81} They showed that incorporation of a phosphorus-containing analogue of the amino acid statine into the oligopeptide sequences significantly increased inhibition of the prototypical aspartic peptidase pepsim. During the course of the investigations, they discovered that the more effective inhibitor for each pair of the diastereomers was the $\lambda$-configuration (Table 2).

Several aminophosphonic acids were found to be very selective and potent inhibitors toward other endopeptidases. B. Vincent’s research group published the biological studies of a series of selective and potent phosphinic peptide inhibitors of endopeptidase 3.4.24.16.\textsuperscript{82} This research showed that the most selective peptide analog, Pro-Phe-$\psi$(\text{PO}_2\text{CH}_2)$-Leu-Pro-NH_2$, displayed a $K_i$ value of 12 nM. In comparison to the related endopeptidase 3.4.24.15 tested, the inhibitor was 550-fold less effective; furthermore, compared to other enzymes (endopeptidase 3.4.24.11, aminopeptidases B and M, dipeptidylaminopeptidase IV or proline endopeptidase), no inhibition was observed.

Phosphonic acid derivatives have also been utilized as inhibitors of metalloproteinases. Matrix metalloproteinases (MMPs) are zinc-dependent proteolytic enzymes. They contain a zinc cation (Zn\textsuperscript{2+}) that plays both a catalytic and structural role.\textsuperscript{83} There are over 30 types of metalloproteinases involved in many physiological and pathological remodeling and degradation processes of extracellular matrix components.\textsuperscript{84} In many cases, a change in MMP function causes a pathological state; they are also implicated in many diseases including cancer,\textsuperscript{85} osteoporosis,\textsuperscript{86} arthritis,\textsuperscript{87} arteriosclerosis,\textsuperscript{88} multiple sclerosis,\textsuperscript{89} and liver cirrhosis.\textsuperscript{90} Fosinopril 61 was one of the first phosphorus-based MMP inhibitors clinically used for the treatment of hypertension and some types of chronic heart failure by inhibition of ACE (angiotensin converting enzyme).\textsuperscript{91} Fosinopril is administered as a prodrug and converted in vivo to the active form fosinoprilat 62. Direct administration of the drug in its active form does not guarantee effective treatment because fosinopril is ionic under physiological conditions, and its oral bioavailability is thus very low.

In 1999, Vassiliou and coworkers reported the synthesis and biological studies of a series of phosphinic pseudo-tripeptide inhibitors against MMP-1, MMP-2, MMP-7, MMP-8, MMP-11, and MMP-14.\textsuperscript{92} They demonstrated the structure–activity relationships regarding the influence of different substituents at the P1', P2 and P2' position. The inhibitors were highly potent towards MMPs, displaying nanomolar $K_i$ values. For MMP-8, replacement of the benzyl group at the P1' position by phenylpropyl (RXP03) 63 caused a 30-fold increase in potency (Fig. 11).

Yiotakis and coworkers published the synthesis of a phosphinic pseudopeptide series containing a variety of P1-side chains.\textsuperscript{93} The new compounds were tested as potential selective inhibitors against MMP-2, MMP-7, MMP-8, MMP-9, MMP-11, MMP-13, and MMP-14. Several phosphinic inhibitors displayed high selectivity toward MMP-11; the greatest potency was exhibited by compound 64 with a $K_i$ value of 0.23 $\mu$M.

In 2003, scientists from France and Greece reported the solution-phase synthesis of new phosphinopeptide inhibitors.\textsuperscript{94} Promising results were observed for RXP03, which was modified at the P1' position by introducing an isoxazole group to obtain 65.

Table 2  Binding of tripeptide and tetrapeptide analogues 59–60 to pepsin

<table>
<thead>
<tr>
<th>Inhibitor</th>
<th>$K_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iva-$\alpha$-Sta$^b$-Ala-Iaa 59A</td>
<td>25 $\mu$M</td>
</tr>
<tr>
<td>Iva-$\lambda$-Sta$^b$-Ala-Iaa 59B</td>
<td>0.9 $\mu$M</td>
</tr>
<tr>
<td>Iva-Val-$\alpha$-Sta$^b$-Ala-Iaa 60A</td>
<td>200 nM</td>
</tr>
<tr>
<td>Iva-Val-$\lambda$-Sta$^b$-Ala-Iaa 60B</td>
<td>&lt;0.07 nM</td>
</tr>
</tbody>
</table>

Fig. 11  Chemical structures of aminophosphonic acid derivatives 61–66.
Research showed that compound 65 was 36-fold more active than RXP03 63 towards MMP-14. The investigation suggested that the P1’ substituent was responsible for the high potency and selectivity of these MMP inhibitors. Compound 65 was highly stereospecific; biological studies showed that the (R, S, S) di- stereoisomer was 100-fold more active than the (R, R, S) isomer.

In 2005, Italian scientists reported the synthesis of three novel peptidomimetic phosphate inhibitors and evaluated their biological activity towards metalloproteinases MMP-2 and MMP-8. All of the compounds were highly potent showing IC₅₀ values in the micromolar range. The greatest activity was observed for inhibitors 66 against MMP-2.

The latest research reported the application of aminophosphinic acid derivatives for the treatment of Alzheimer’s disease. They are classified as the inhibitors of β-secretase, an aspartic acid protease important in the formation of myelin sheaths in peripheral nerve cells. Until 2007, several pharmaceutical companies were in the early stages of testing new drugs for the treatment of Alzheimer’s disease. In 2012, Merck reported the results of a phase I trial for MK-8931 67 and started a new clinical trial to evaluate the safety and effectiveness of this compound in patients with mild-to-moderate Alzheimer’s disease. Phosphinic acid derivatives 68 as potential β-secretase inhibitors were first described in 2006. The authors of the patent reported that the synthesized inhibitors had high activity toward the enzyme with IC₅₀ values in the range of 0.01–0.2 μM (Fig. 12).

5.2. α-Aminophosphonic acid derivatives

A series of α-amino phosphonic acids are a significant type of compounds that contain a P–C bond. These class of molecules are known as effective chelating agents. The presence of a –NH₂C–P(O)(OH)₂ group increases their metal binding abilities. Many synthetic methods for the preparation of aminophosphonic acid derivatives have been described. Although aminophosphonic acids were mainly used as insecticides, herbicides, and plant-growth regulators, they have also been applied as effective chemotherapeutic agents.

A number of reports have been published on phosphonic acid derivatives used as MMP inhibitors. Hunter and coworkers reported the synthesis of a series of peptidomimetic α-aminophosphonic acid derivatives with high inhibitory properties against human fibroblast collagenase and carried out in vitro tests for these compounds. Introduction of a bromophthalimidoethyl group into the structure led to a very potent inhibitor 69 with an IC₅₀ value of 0.02 μM. The (R, S, S) isomer of 69 was much more potent (80-fold) than the (S, S, S) isomer towards MMP-1.

In 1999, D’Alessio and coworkers synthesized and evaluated peptidomimetic N-(furan-2-yl)carbonyl-Leu-Trp-OH analogues. The compounds were tested for their activity against MMP-2, MMP-3, MMP-8, and MMP-9. The study showed that most peptidomimetic derivatives exhibited low potency towards MMPs. Nevertheless, compound 70 exhibited high activity with a satisfactory IC₅₀ value of 60 nM.

Gallina et al. prepared a series of new phosphonic acid derivatives 71 by modifying the previously reported phosphotryptophan derivative i-Pro-i-Leu-i-[P]Trp(OH)₂. By replacing the aminoterminal i-Pro with amino acid residues bearing small side chains, the affinity to MMP-2 and MMP-8 was increased, and the derivatives showed different selectivity profiles (Fig. 13).

In 2009, Tortorella and coworkers obtained new α-sulfonophosphonate analogues. Preliminary activity screening of these compounds was investigated against MMP-2, MMP-8, MMP-13, and MMP-14. Most of the synthesized analogues were very effective MMP inhibitors, exhibiting IC₅₀ values in the nanomolar range. Derivative 72 proved to be the most potent inhibitor towards MMP-2 with an IC₅₀ = 60 nM.

The Mazza research group prepared new α-arylsulfonylaminophosphonates and tested them as stereoselective inhibitors of MMP-8. The mechanism of binding in the active site for both the R- and S-enantiomers (73 and 74, respectively) was explained by analyzing the crystal structures of the complexes with MMP-8. The study showed that enantiomer R 73 was much more potent than the S enantiomer 74 with an IC₅₀ value in the nanomolar range.

Another class of phosphonic acid-based MMP inhibitors are the carbamoylphosphonic acid derivatives. A collaboration of scientists from Israel and Germany reported the synthesis, characterization and biological evaluation of the alkyl and cycloalkylcarbamoylphosphonic acid analogues. Their inhibition potency was tested in in vitro models with MMP-1, MMP-2, MMP-3, MMP-8, and MMP-9. The cycloalkylcarbamoylphosphonic acid derivatives exhibited higher

**Fig. 12** Structures of β-secretase inhibitors MK-8931 67 and 68.

**Fig. 13** Chemical structures of aminophosphonic acid derivatives 69–75.
potency compared to the open-chain alkyl analogs. Most of the analogs showed good selectivity against MMP-2. The optimal activity against MMP-2 was observed for compound 75 with an IC_{50} value of 0.08 \mu M. In 2005, the same research group reported\(^{106}\) that cycloalkylcarbamoylphosphonic acid-based inhibitors that block MMP-2 activity have a significant impact on the inhibition of tumor cell growth and reduce lung metastasis. This investigation proved that new carbamoyl phosphate matrix metalloproteinase inhibitors might be effective drug candidates for cancer treatment.

In 2004, Breuer and coworkers prepared novel MMP inhibitors based on Ca\(\text{[n]}\), Mg\(\text{[n]}\), Zn\(\text{[n]}\) and Cu\(\text{[n]}\) complexes of cyclopentylcarbamoylphosphonic and 2-(N,N-dimethylamino) ethylcarbamoylphosphonic acids (76 and 77, respectively)\(^{107}\). Both carbamoyl phosphonates showed very high MMP-2 activity with IC_{50} values of 80 nM for compound 76 and 25 nM for analog 77. During the study, it was found that the dimethylamino group on compound 77 enhanced the binding potency of zinc binding group (ZBG) in aqueous solutions (Fig. 14).

In 2008, the Hoffman research group presented the synthesis of cis-2-aminocyclohexylcarbamoylphosphonic acid (cis-ACCP) \(^{78}\) and analyzed its pharmacodynamic and pharmacokinetic properties.\(^{108}\) Cis-ACCP was evaluated in in vitro and in vivo cancer metastasis models and classified as a medium-potency MMP inhibitor; because of its good pharmacological profile, this molecule entered phase 2 and 3 clinical trials (Fig. 15).

Recently, this laboratory\(^{109}\) presented the synthesis of seven 4-phenoxyphenzenesulfonamidopolymethylene carbamoyl phosphonates \(^{79}\) containing polymethylene chains. Biological evaluation of these compounds showed the highest potency for analogues with \((\text{CH}_{2})_{5,6}\) groups, which exhibited antitumoractivity in a murine melanoma model. Compounds with shorter polymethylene linkers were selective towards MMP-2 in contrast to the analogs bearing chains with 7 or 8 methylene groups, for which no inhibitor activity was observed.

The latest achievements in the development of aminophosphonic acids with biological activity are the synthesis and application of chiral thiourea derivatives. They are an important class of compounds that demonstrate potential antibacterial, fungicidal, antiviral (including HIV) and anticancer activity. Several of them have found practical application as herbicidal compounds or plant growth regulators.\(^{110}\) Currently, the use of chiral thiourea derivatives to treat disease is the subject of intense research.

6. Phosphorus compounds with antiviral activity

Development of new antiviral therapy is needed to treat viral infections that are not amenable to prophylaxis by vaccination or did not fulfill its promises for complete protection, but is also highly desirable for those infections where vaccination has not been implemented. The beginning of the antiviral era is marked by the description in 1959 of the synthesis of 5-iodo-2'-deoxyuridine (IDU).\(^{111}\) IDU was actually synthesized as a potential antitumor agent, but later became commercialized as the first antiviral drug to be used in the topical treatment of herpetic eye infections. Nowadays, among the drugs used in treatment of some viral infections e.g. human immunodeficiency virus (HIV), hepatitis C virus (HCV), hepatitis B virus (HBV), cytomegalovirus (CMV), smallpox (variola virus) there are many compounds containing a phosphorus atom.

Nowadays, AIDS, caused by HIV infection is one of the major medical problems. According to the WHO data, 36.9 million people were living with HIV and 1.9 million people newly enrolled on antiretroviral treatment in 2014. In 1985, E. de Clercq et al., described the activity of 9-(\(R\))-2-phosphonomethoxypropyladenine (tenofovir) \(^{80}\) against HIV in cell culture.\(^{112}\) Tenofovir is a nucleotide (nucleoside monophosphate) analogue with activity against retroviruses, including HIV-1, HIV-2 and hepadnaviruses in a variety of cell types, including resting cells. Tenofovir is administered to patients in the form of a prodrug – tenofovir disoproxil fumarate (tenofovir DF) \(^{81}\). Following absorption, tenofovir DF is rapidly converted to tenofovir (Fig. 16), which is metabolised intracellularly to its active anabolite, which is a competitive inhibitor of HIV-1 reverse transcriptase and terminates the growing DNA chain.\(^{113}\)

Continuing research into more active agents led to the discovery of other derivatives of tenofovir with better distribution into lymphoid tissues. GS-7340 \(^{82}\) is a prototype molecule representing a novel class of tenofovir monophosphonamidate prodrugs. Unlike tenofovir, GS-7340 contains phenol and alanine isopropl ester as the phosphate masking groups. Relative to parent tenofovir, GS-7340 exhibits 500- to 1000-fold enhanced activity against HIV-1 in...
T-cells, activated peripheral blood mononuclear lymphocytes and macrophages.114

There are currently a large number of agents in development across a variety of classes for the treatment of HCV infections. One class for which promising in vitro results have been reported is represented by the nucleoside/nucleotide analogs. These compounds share properties with the intracellular nucleoside substrates of the target HCV enzymes involved in the transcription of the viral genome and, when phosphorylated to the nucleoside-triphosphate, lead to premature termination of the growing HCV RNA chain during viral replication.115 One of nucleotide analog, sofosbuvir 83 is a phosphonamidate prodrug that is metabolized within the liver into the active antiviral agent 2'-deoxy-2'-α-fluoro-β-C-methyluridine-5'-monophosphate 84 which is further phosphorylated to the active 2'-deoxy-2'-α-fluoro-β-C-methyluridine-5'-triphosphate 85 (Fig. 17).116 The triphosphate serves as a defective substrate for the NS5B protein, which is the viral RNA polymerase, thus acts as an inhibitor of viral RNA synthesis.117 In 2013, the Food and Drug Administration (FDA) approved sofosbuvir in combination with ribavirin for oral dual therapy of HCV genotypes 2 and 3, and for triple therapy with injected pegylated interferon and ribavirin for treatment-naive patients with HCV genotypes 1 and 4. In 2014 a combination of sofosbuvir with the viral NS5A inhibitor ledipasvir was approved.

Hepatitis B is another viral infection that attacks the liver and can cause both acute and chronic disease. According to the WHO data, an estimated 240 million people worldwide are chronically infected with HBV. More than 780 000 people die every year due to complications of hepatitis B, including cirrhosis or liver cancer.118 Adefovir 86 is a drug used to treat infections with hepatitis B virus. It is a nucleotide analog with reverse transcriptase inhibitory activity. Adefovir is orally administrated as a prodrug – adefovir dipivoxil 87. After administration adefovir dipivoxil is hydrolysed to adefovir and phosphorylated to its active diphosphorylated form adefovir dipivoxil 88 (Fig. 17). Upon phosphorylation, adefovir DP competes with dATP for incorporation by the HBV reverse transcriptase. The lack of a 3'-hydroxyl group causes chain-termination when adefovir is incorporated into viral transcripts.119 Dose of 10 mg per day of adefovir dipivoxil significantly improved histological, biochemical and virological outcomes in HBeAg-positive and – negative patients, and serological outcomes in HBeAg-positive patients.120

Treatment of CMV infections in immunosuppressed patients based upon several compounds including foscarnet 89 and cidofovir 90. Both compounds are administered intravenously [foscarnet at 180 mg kg⁻¹ per day for induction therapy and at 120 mg kg⁻¹ per day for maintenance therapy; cidofovir at 5 mg kg⁻¹ per week during the first 2 weeks (induction therapy), and then 5 mg kg⁻¹ every other week (maintenance therapy)]. Foscarnet and cidofovir are targeted at the viral DNA polymerase. Foscarnet interacts directly with the pyrophosphate binding site of the DNA polymerase, whereas cidofovir must be first phosphorylated to its diphosphate derivative, which then interact as competitive inhibitor/alternate substrates. As alternate substrate phosphorylated cidofovir is incorporated into the growing DNA chain and block chain elongation (Fig. 18).121

With the declaration by WHO in 1980 that smallpox had been eradicated from the earth, any attempts to develop a potentially active anti-poxvirus drug were abandoned. In 2001, the fear that variola virus might emerge again as the consequence of a terrorist attack. In the US a program was launched to identify antiviral agents that could be used prophylactically or therapeutically against orthopoxviruses, which could be employed as a biological weapon or to give arise to an inadvertent outbreak. One of the foremost candidate to be used in such scenario is CMX-001 91. CMX-001 is the hexadecyloxypropyl ester of cidofovir, which had already been reported as an antiviral agent active against vaccinia virus. CMX-001 is a highly promising compounds to treat pathogenic orthopoxvirus infection in humans and should not only be intended for therapeutic use against smallpox, but also for progressive vaccinia as the consequence of the smallpox vaccination (in immunosuppressed patients); monkeypox, where cidofovir has proved more efficacious than vaccination; and even molluscum contagiosum (due to mollusceipoxvirus).4

7. Conclusions

This literature review has emphasized and described the importance of organophosphorus derivatives, which are a wide class of chemical compounds containing organic moieties usually bonded directly to phosphorus or bonded through a heteroatom, such as sulfur, oxygen or nitrogen. As discussed in this literature review, medical applications of organophosphorus compounds as drugs or drug candidates against many diseases have expanded greatly in recent years. OPs are used in clinical practice as compounds with anticancer or antiviral

![Fig. 17](image1.png)  
**Fig. 17** Activation mechanism of sofosbuvir 83 and adefovir 86.

![Fig. 18](image2.png)  
**Fig. 18** Structures of foscarnet 89, cidofovir 90 and CMX-001 91.
properties. Bisphosphonates are currently the most important and effective class of drugs developed for the treatment of metabolic bone disorders associated with increased osteoclast-mediated bone resorption, such as osteoporosis. Aminophosphinic and aminophosphonic acids also are a very important group of chemical compounds, and their synthesis has attracted considerable attention in medicinal chemistry. They are classified as antimetabolites, which compete with their aminocarboxylic acid analogues in the active sites of enzymes and other cell receptors. It is without a doubt because of the unique properties and various applications of organophosphorus compounds that will continue to make them the subject of intense research investigations around the world.

List of abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>ACE</td>
<td>Angiotensin converting enzyme</td>
</tr>
<tr>
<td>CA4P</td>
<td>Combretastatin A-4 phosphate</td>
</tr>
<tr>
<td>CMV</td>
<td>Cytomegalovirus</td>
</tr>
<tr>
<td>CWA</td>
<td>Chemical warfare agents</td>
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<tr>
<td>FDA</td>
<td>Food and drug administration</td>
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<tr>
<td>HBV</td>
<td>Hepatitis B virus</td>
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<td>HCV</td>
<td>Hepatitis C virus</td>
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<tr>
<td>HIV</td>
<td>Human immunodeficiency virus</td>
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<tr>
<td>IDU</td>
<td>5-Iodo-2’-deoxyuridine</td>
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<tr>
<td>MMPs</td>
<td>Matrix metalloproteinases</td>
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<tr>
<td>OPs</td>
<td>Organophosphorus compounds</td>
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<tr>
<td>PAN</td>
<td>Pesticide action network</td>
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<td>SERMs</td>
<td>Specific estrogen receptor modulators</td>
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<tr>
<td>STS</td>
<td>Steroid sulfatase</td>
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<tr>
<td>TEPP</td>
<td>Tetraethyl pyrophosphate</td>
</tr>
<tr>
<td>thioTEPA</td>
<td>$N,N',N''$-Triethylenetriphosphoramidide</td>
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<td>WHO</td>
<td>World health organization</td>
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<tr>
<td>ZBG</td>
<td>Zinc binding group</td>
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References
