

The ProTide Prodrug Technology: From the Concept to the Clinic

Miniperspective

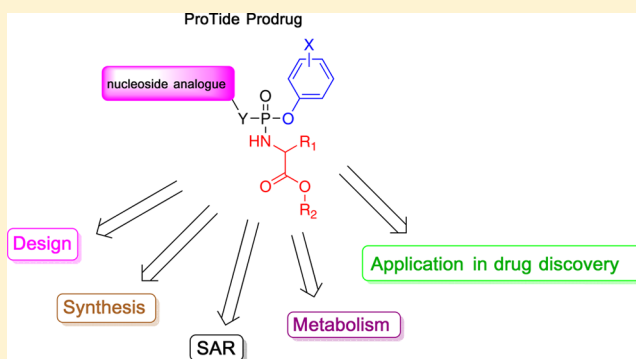
Youcef Mehellou,^{*,†} Hardeep S. Rattan,[‡] and Jan Balzarini^{*,§}

[†]School of Pharmacy and Pharmaceutical Sciences, Cardiff University, Redwood Building, Cardiff CF10 3NB, U.K.

[‡]School of Pharmacy, College of Medical and Dental Sciences, University of Birmingham, Edgbaston, Birmingham B15 2TT, U.K.

[§]Laboratory of Virology and Chemotherapy, Rega Institute for Medical Research, Herestraat 49, 3000 Leuven, Belgium

ABSTRACT: The ProTide technology is a prodrug approach developed for the efficient intracellular delivery of nucleoside analogue monophosphates and monophosphonates. In this approach, the hydroxyls of the monophosphate or monophosphonate groups are masked by an aromatic group and an amino acid ester moiety, which are enzymatically cleaved-off inside cells to release the free nucleoside monophosphate and monophosphonate species. Structurally, this represents the current end-point of an extensive medicinal chemistry endeavor that spans almost three decades. It started from the masking of nucleoside monophosphate and monophosphonate groups by simple alkyl groups and evolved into the sophisticated ProTide system as known today. This technology has been extensively employed in drug discovery, and it has already led to the discovery of two FDA-approved (antiviral) ProTides. In this work, we will review the development of the ProTide technology, its application in drug discovery, and its role in the improvement of drug delivery and efficacy.



1. INTRODUCTION

Nucleoside analogues were first introduced a number of decades ago as an effective way of treating various diseases such as cancer and viral infections like herpes simplex virus (HSV), human cytomegalovirus (HCMV), human immunodeficiency virus (HIV), hepatitis B virus (HBV), and recently also hepatitis C virus (HCV).^{1–6} Currently, there are more than 20 different nucleoside analogues available in the clinic to treat the viral infections and cancer.^{7,8} These molecules enter the cell with the aid of transporters such as concentrative nucleoside transporters as well as peptide transporters or via passive diffusion.^{9,10} Once inside the cell, the nucleoside analogues are activated by a number of nucleoside and nucleotide kinases which phosphorylate them in a stepwise manner resulting in the formation of the mono-, di-, and triphosphorylated nucleoside analogue metabolites (Figure 1).^{6,11}

The activated (phosphorylated) antiviral nucleoside analogues exert their therapeutic effects by targeting and inhibiting intracellular enzymes (usually the virus-encoded DNA or RNA polymerases) and/or by being incorporated into the viral nucleic acid chains leading to the termination of the elongation process.^{7,8,12} However, there are a number of limitations associated with the administration of nucleoside analogue drugs. Nucleoside analogues are structurally different to natural nucleosides, making their phosphorylation by cellular or viral kinases often inefficient.^{13,14} This ultimately limits the formation of the active triphosphate metabolites, often the nucleoside analogue active metabolite.¹³ They also often

demonstrate poor oral bioavailability due to their low intestinal permeability, as they are usually polar molecules that hinder their transport through the cell border via the paracellular route.¹⁵ Additionally, the therapeutic use of many antiviral and anticancer nucleoside analogues is further limited by resistance, which occurs via a number of mechanisms⁸ that include (1) down regulation of the nucleoside kinases responsible for activating nucleoside analogues,¹⁶ (2) depletion of transporters that affect their efficient trafficking into the target cells,^{17–19} (3) activation of phosphatases (i.e., 5'-nucleotidases) that dephosphorylate the active metabolites of nucleoside analogues,^{20,21} and (4) increased catabolic bioconversion of the nucleoside analogues, e.g. (deoxy)cytidine deamination, which may yield inactive versions of some of the nucleoside analogues.^{22,23}

To overcome these limitations, it was initially suggested that delivering phosphorylated metabolites of the nucleoside analogue would address some of these shortages. This notion was further supported by numerous studies that reported the poor phosphorylation of nucleoside analogues into their nucleoside monophosphates as the rate-limiting step in their *in situ* activation.^{24–27} However, the idea of using nucleoside analogue monophosphates as therapeutics faced two main challenges. First, these compounds would have poor *in vivo* stability due to dephosphorylation in the bloodstream, and second, their transport into cells will be inefficient because of

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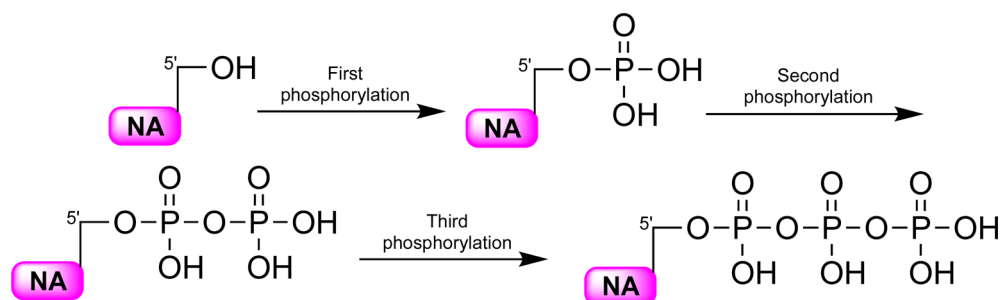


Figure 1. Intracellular activation of therapeutic and experimental nucleoside analogues. NA: nucleoside analogue.

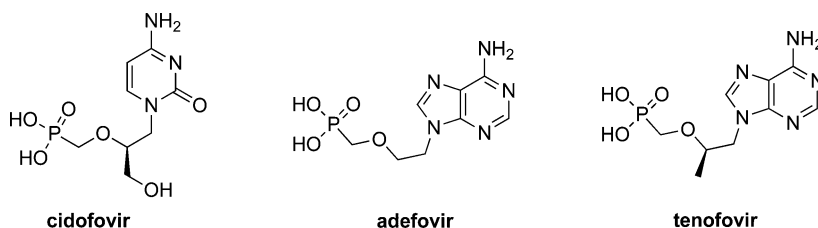


Figure 2. Chemical structures of therapeutic nucleoside analogue monophosphonates, cidofovir, adefovir, and tenofovir.

the charged nature of the phosphorylated nucleoside. To address the P–O– bond instability, Holý and De Clercq switched the P–O– bonds in the monophosphate group of nucleoside analogues into monophosphonate P–CH₂– bonds.²⁸ This led to improved in situ stability, which translated into longer half-lives of the nucleoside monophosphonates as compared to their monophosphates.²⁸ This advance in the design of stable nucleotide therapeutics inspired the discovery of many nucleoside analogue monophosphonates, some of which were eventually approved for clinical use as antivirals against HCMV [i.e., cidofovir], HBV [i.e., adefovir and tenofovir], and HIV [i.e., tenofovir] (Figure 2).⁷

Although the use of monophosphonates efficiently addressed the in situ and in vivo instability issue associated with monophosphate (P–O–) bonds, these compounds still had poor cellular uptake due to the negative charges on the monophosphonate group at physiological pH (<7.4). This limitation acted as a challenge in the medicinal chemistry field to develop prodrugs of nucleoside analogue monophosphates and monophosphonates that can deliver them into cells more efficiently. Numerous prodrug technologies that mask either one or two of the oxygens of the monophosphate and monophosphonate groups making the molecule more lipophilic and hence improve transport into the cells have been developed.^{13,29–31} Among these prodrug approaches is the ProTide prodrug technology that was pioneered by Prof. Chris McGuigan (Cardiff, UK).³² This prodrug technology has proved to be a powerful tool in the discovery of efficacious nucleoside monophosphate and monophosphonate prodrug therapeutics.³³ To date, it has delivered at least 10 clinical candidates that reached, or successfully passed, phase I clinical trials.³³ Although most of these nucleotide prodrugs were developed as antiviral agents against HIV, HBV, HCV, and Ebola virus, the most recent ones are also being pursued as potential anticancer agents. Moreover, the ProTide prodrug technology has so far led to the discovery of two FDA-approved (antiviral) drugs, tenofovir alafenamide (TAF)³⁴ and sofosbuvir³⁵ (Figure 3).¹³

Because of the effectiveness of the ProTide technology in the in vivo intracellular delivery of nucleoside analogue mono-

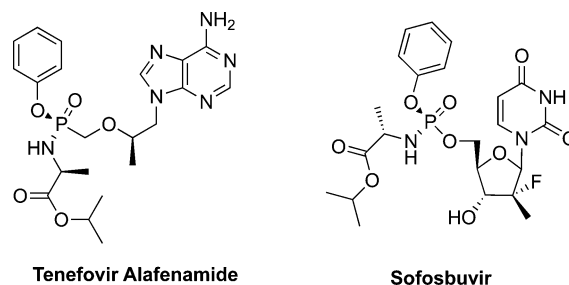


Figure 3. Chemical structures of the two FDA-approved antiviral ProTides, tenofovir alafenamide (TAF) and sofosbuvir.

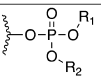
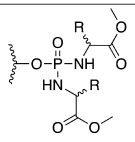
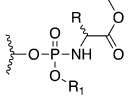
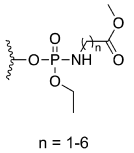
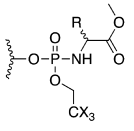
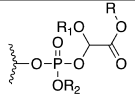
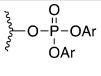
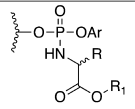
phosphates and monophosphonates, there has been a growing interest in the application of this technology in drug discovery. The last comprehensive review on the development of the ProTide technology appeared in 2009 (Mehellou, Balzarini and McGuigan).³² However, at that time, the ProTides had just entered clinical trials and significant advances in their synthesis, metabolism, and clinical studies have been achieved since then. Thus, we felt that there is a need for an updated and comprehensive report on the ProTide technology, which this review aims to address and therefore provide a much needed updated resource for the scientific community.

2. INCEPTION AND EVOLUTION OF THE PROTIDES

Initial work on the ProTides can be tracked to the late 1980s.^{36–38} The mission was to mask the oxygen atoms of phosphate groups in nucleoside monophosphate analogues so that they are neutral at physiological pH and hence have a better uptake into cells. The process started from the simple masking of the phosphate groups by alkyl groups but eventually evolved into the intelligent masking of the phosphate with aryl groups and amino acid esters, which can be cleaved off inside the intact cells. Such a development process, which took at least two decades, could be divided into six phases as discussed below.

Stage One: Alkyl and Haloalkyl Phosphate Esters. The first attempt of making nucleoside analogue monophosphate prodrugs was to mask the phosphate group of 9-β-D-

Table 1. Stages of the Development of the ProTide Prodrug Technology

Stages of development	Phosphate masking group(s)	Stages of development	Phosphate masking group(s)
1. Alkyl and haloalkyl phosphate triesters	 <p>R_1 and $R_2 = \text{Me, Et, Pr, } -\text{CH}_2\text{CCl}_3 \text{ and } -\text{CH}_2\text{CF}_3$</p>	3. Phosphorodiamidates	 <p>$R = \text{H, Me, iPr, } -\text{CH}_2\text{Ph}$ or $-\text{CH}_2\text{CO}_2\text{CH}_3$.</p>
2. Alkyloxy phosphoramidates	 <p>$R = \text{H, Me, } -\text{CH}(\text{CH}_3)_2, -\text{CH}_2\text{CH}(\text{CH}_3)_2, -\text{CH}(\text{CH}_3)\text{Et}$ or Bn</p> <p>$R_1 = \text{Me, Et, Pr, Bu}$ or Hex</p>  <p>$n = 1-6$</p>  <p>$R = \text{H, Me}$ or iPr</p> <p>$X = \text{H, F}$ or Cl</p>	4. Lactyl-derived systems	 <p>$R = \text{Me}$ or Et, $R_1 = \text{H}$ or Me, $R_2 = \text{Me, nPr}$ or $\text{nC}_{12}\text{H}_{25}$.</p>
		5. Diaryl phosphates	 <p>$\text{Ar} = \text{Ph}$ or $p\text{-X-Ph}$</p> <p>($x = \text{various}$)</p>
		6. Aryloxy phosphoramidates	 <p>$\text{Ar} = \text{Ph}$ or substituted Ph</p> <p>$R = \text{H, Me, } -\text{CH}_2\text{iPr, } -\text{CH}_2\text{Ph...etc.}$</p> <p>$R_1 = \text{Me, Et, iPr, tBu, Bn...etc.}$</p>

arabinofuranosyladenine (AraA)³⁹ monophosphate, which exerts antiviral activity, by simple dialkyl triesters (Stage 1, Table 1).³⁶ Although these prodrugs led to increased stability toward adenosine/adenylate deaminases, they demonstrated a moderate biological activity.³⁶ Similar results were found when the same principle was applied to the anticancer agent 1- β -D-arabinofuranosylcytosine (AraC).^{37,40} However, when the dialkyl phosphate approach was used to mask the monophosphate group of the anti-HIV agent 3'-azidothymidine (AZT),⁴¹ no significant activity was observed in vitro.⁴² This was attributed to several parameters, but the most likely explanation for the lack of activity was due to the high stability of the dialkyl triesters, which hindered the eventual conversion to the biologically active 5'-O-triphosphate form of AZT.⁴³ Masking the monophosphate groups of AZT and 2',3'-dideoxycytidine (ddC)⁴⁴ with haloalkyl derivatives also yielded agents with poor biological activity.⁴⁵ To enhance the intracellular cleavage of the haloalkyl masking groups, more haloalkyl phosphate masking groups with halogen atoms incorporated either on one or in both masking groups were used for making AZT monophosphate prodrugs. However, these prodrugs also displayed moderate antiviral activities.⁴⁶ However, the use of haloalkyl groups in AraA and AraC monophosphates displayed significant increases in biological activity (Stage 1, Table 1).⁴⁷ This increase in activity was mainly attributed to increased lipophilicity, resulting in better membrane permeability of the prodrug.⁴⁷ The lack of increased AZT activity through administration of haloalkyl prodrugs of AZT could now be explained by the fact that the first phosphorylation step of AZT is not the rate-limiting step in its activation pathway while it certainly is for AraA and AraC.⁴⁸

Nevertheless, the alkyl and haloalkyl phosphate masking groups, especially for their application to AraA and AraC, indicated that these masking groups showed good activity due to better membrane-crossing ability, because the biological activity correlated with lipophilicity, rather than increased intracellular levels of the phosphate species.^{36,37,47} Such conclusion shifted the thinking toward phosphate prodrugs to a different strategy.

Stage Two: Alkyloxy and Haloalkyloxy Phosphoramidates. Subsequently, the design of nucleoside phosphate prodrugs focused on alkyloxy and haloalkyl phosphoramidate prodrugs (Stage 2, Table 1). The move toward phosphoramidate prodrugs was provoked by the findings that the HIV protease can cleave an oligopeptide from the phosphate group of blocked nucleotide phosphoramidates.⁴⁹ Initially, a selection of AZT alkyloxy phosphoramidates with methyl-esterified amino acids were synthesized.⁴² These compounds showed better anti-HIV activity than the dialkyl AZT prodrugs.⁴² Although the anti-HIV activity did not correlate with the alkyl phosphate chain, it did correlate with the amino acid side chain, with L-alanine showing the better activity.^{42,50} Retrospectively, this observation proved to be critical for the success of the ProTide technology in drug discovery since all of the ProTides that entered clinical trials and those that have been approved for clinical use bear an L-alanine moiety.³³ Further studies into different, i.e. α , β , and γ , types of amino acids, indicated the superiority of α -amino acids.⁵¹

Encouraged by the influence of the amino acid moiety on the anti-HIV activity of AZT alkyloxy phosphoramidates, the masking of phosphate groups by the methyl-esterified amino acids and haloalkyl groups, which increased the membrane-

crossing ability, were explored next. Haloalkyl phosphoramidates of AZT were synthesized with glycine, alanine, and valine amino acids as well as ethyl, trifluoroethyl, or trichloroethyl as the haloalkyl motifs.⁵² These, surprisingly, did not show good anti-HIV activity with the exception of the trichloroethyl alanine prodrug. Because no clear structure–activity relationship was apparent from the haloalkyl phosphoramidates, they were not pursued any further. However, the key finding of the enhancement of activity with nucleoside phosphoramidate prodrugs, especially with L-alanine, proved to be important for the future evolution of this nucleoside monophosphate prodrug strategy.

Stage Three: Phosphorodiamidates. Given that the introduction of amino acids to generate phosphoramidates led to enhanced anti-HIV activity, it was logical that the next step would be to mask both oxygen groups of the phosphate group by amino acid esters. Indeed, a series of amino acid methyl esters with different side chains were used to mask both oxygens of the phosphate group of AZT monophosphate (Stage 3, Table 1).⁵³ Unlike previous studies, where L-alanine appeared to give the better biological activity, in these phosphorodiamidate systems amino acids with aromatic side chains, e.g., phenylalanine, showed better improvement of biological activity.⁵³ Although this was surprising in the context of the ProTides' development, such finding was consistent with other studies where a preference was found for amino acids with aromatic side chains in the development of unrelated phosphoramidate diesters.^{29,31} Although no further studies with these phosphorodiamidates were conducted since the early 1990s and the development of the ProTides moved on, phosphorodiamidates as phosphate prodrugs recently (in 2011) made a comeback.⁵⁴

Stage Four: Lactyl-Derived Systems. Continuing with the probing of the phosphoramidates and particularly studies on the importance of the P–N bond, isosteric O-linked nucleoside analogues derived from lactic and glycolic acids of AZT were prepared and evaluated for their biological activity (Stage 4, Table 1).⁵⁵ Although no significant improvement in the anti-HIV activity was noted for the lactyl-derived AZT monophosphate prodrugs, the observed activity was found to correlate with the lengthening of the alkyl phosphate chain (R_2) because longer chains resulted in poorer anti-HIV activity. As for the glycol systems ($R_1 = H$), the prodrugs were generally more active than the lactyl systems. The poor anti-HIV activity of these phosphate prodrug systems was not very encouraging, and they were therefore not optimized or explored any further.

Stage Five: Diaryl Phosphates. The next masking groups studied in the design of a novel phosphate prodrug strategy were aryl motifs. Indeed, the masking of AZT monophosphate by diaryl motifs was pursued (Stage 5, Table 1).⁵⁶ These prodrugs showed good anti-HIV activity and, remarkably, some of them showed much better anti-HIV activity than the parent compound AZT.⁵⁶ In the journey toward the ProTides, this was the first time a phosphate prodrug was more active than the parent compound. Interestingly, these phosphate prodrugs retained their anti-HIV activity in cell lines that were considered to be resistant to AZT.⁵⁶ However, when these cells (T lymphocyte cell line, JM) were used for this study back in 1992, they were considered as AZT insensitive due to poor phosphorylation of AZT.⁵⁷ But, it was later shown that such AZT resistance was a result of an active AZT-efflux pump rather than inefficient intracellular phosphorylation.⁵⁸ Regardless of the exact AZT-insensitivity mechanism in this cell line,

the AZT diaryl phosphate prodrugs were more active than their parent compound, providing a clear indication of an increased delivery of AZT monophosphate into the cells. This notion was further supported by the fact that *para*-nitrophenyl phosphate masking groups had ca. 100-fold better anti-HIV activity than their unsubstituted phenyl masking groups most probably due to the electron-withdrawing effect of the *para*-nitro group that speeds up the demasking of the prodrugs in cells.⁵⁶ A further study on the effect of the nature of the phenyl substituents on the antiviral activity of diaryl phosphate prodrugs of AZT was then conducted.^{59,60} This study confirmed that stronger *para*-electron-withdrawing groups on the phenyl phosphate masking groups gave better anti-HIV activity.^{59,60} Intriguingly, these AZT diaryl phosphate prodrugs as well as AZT did not exhibit any anti-HIV activity in a thymidine kinase (TK)-deficient human T-lymphocyte cell line (CEM/TK⁻).⁶⁰ McGuigan and colleagues concluded that this might have been due to poor intracellular release of AZT monophosphate. The development of diaryl monophosphate prodrugs was not progressed any further and the focus turned back to phosphoramidates, which showed good biological activity.⁵⁶

Stage Six: Aryloxy Phosphoramidates (Generally Referred to as ProTides). Inspired by the improvement of the biological activities of the earlier examples of nucleoside monophosphate prodrugs, particularly the *para*-substituted aryls and the amino acid esters, McGuigan and co-workers took the next logical step, which was to combine these two masking groups in the design of new monophosphate prodrugs.⁶¹ Indeed, the masking of the AZT monophosphate group with *para*-substituted aryls and an amino acid ester was conducted and these efforts yielded prodrugs that showed improved anti-HIV activity as compared to the parent nucleoside AZT. In particular, the combination of a phenyl and L-alanine methyl ester showed the most potent anti-HIV activity in this study, $EC_{50} = 0.8 \mu M$ (AZT, IC_{50} (toxicity) ca. $100 \mu M$).⁶¹ Interesting structure–activity relationships on these aryloxy phosphoramidate prodrugs emerged from this study. Notably, there was a preference for the L-alanine amino acid as compared to L-leucine (>10-fold) and glycine (>100-fold), while electron-withdrawing *para*-substituted aryls were less potent than their unsubstituted moieties.⁶¹ Further studies into these substitutions concluded that *para*-fluoro aryls did not largely affect the biological activity while *para*-nitro-substitutions had detrimental effects on the biological activity, namely a 100-fold loss in activity.⁶² In a separate study, it was shown that *para*-nitrophenyl-containing nucleoside monophosphate prodrugs were toxic even to uninfected cells.⁶³ Remarkably, AZT aryloxy phosphoramidates retained their anti-HIV activities in thymidine kinase deficient (TK⁻) cells.⁶² These observations provided a direct proof of the ability of aryloxy phosphoramidates to deliver intact nucleoside analogue monophosphates into intact cells. Hence, the masking of nucleoside analogue monophosphates, and monophosphonates with an aryl motif and an amino acid ester, which is nowadays known as the ProTide technology, was extensively pursued in the future discovery of novel antiviral and anticancer nucleotide therapeutics.

3. SYNTHESIS OF THE PROTIDES

Although the synthesis of the aryloxy triester phosphoramidate ProTides has recently been excellently reviewed by Pradere et al.,²⁹ for the completion of this Perspective, we will briefly discuss the different strategies used in the synthesis of the

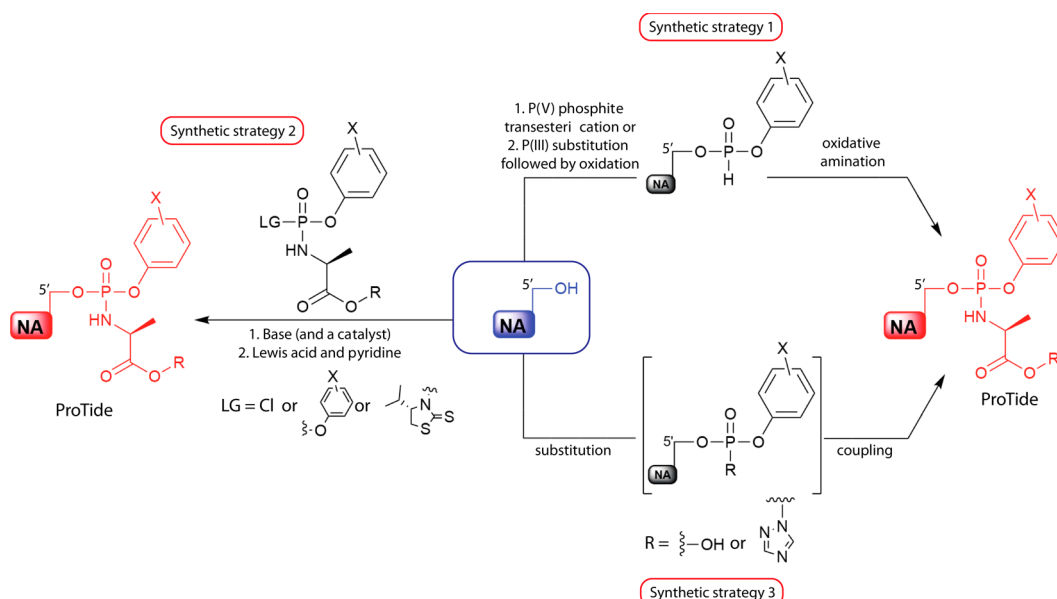


Figure 4. Representation of the three main strategies for synthesizing ProTides. LG: leaving group. NA: nucleoside analogue. R: any ester. X: any aromatic substitution.

ProTides. We will also include recent reports on the development and use of new catalysts that improve the synthesis of the ProTides, which have been published after the comprehensive review by Pradere et al.²⁹ There are three different strategies for synthesizing ProTides: (1) the coupling of a nucleoside with a diarylphosphite followed by subsequent oxidative amination, (2) the coupling of the nucleoside with a phosphorochloridate reagent, and (3) coupling of an amino acid to a nucleoside aryl phosphate (Figure 4).

Among these three strategies, the second synthetic strategy, which involves the coupling of the nucleoside to a phosphorochloridate is the most common method and has been the method of choice of the initial synthesis of the ProTides. The coupling reaction takes place in the presence of either the Grignard reagent *tert*-butyl magnesium chloride (*t*BuMgCl) or *N*-methylimidazole (NMI), which act as a base. The choice of the base is often influenced by the nucleoside substrate, most precisely the number of hydroxyl groups that could couple to the phosphorochloridate. For instance, in ribonucleosides, the base used is often NMI and this generates mostly the 5'-*O*-hosphoramidates due to steric hindrance and the fact that it is a weaker base than *t*BuMgCl. However, in cases where the nucleoside has only one hydroxyl group, the base of choice is *t*BuMgCl, which often gives higher yields of the product as compared to NMI. Notably, the approach of coupling the nucleoside to a phosphorochloridate yields a mixture of diastereoisomers. In some cases, the two ProTide diastereoisomers exhibit similar potency and their development therefore is pursued as a mixture of diastereoisomers (see examples in Figure 10).⁶⁴ In other cases, the two diastereoisomers may have different rates of metabolism and hence varying potency. For instance, the *Sp*-diastereoisomer of the clinically used ProTide sofosbuvir exhibits a 10-fold increase in antiviral activity than its *Rp*-diastereoisomer.³⁵ In these instances, the separation of the two diastereoisomers becomes necessary. The separation of these by column chromatography has proved to be a stern challenge.

To address this, Ross et al.⁶⁵ developed a system that allows for the facile generation and crystallization of single isomer

phosphoramidating reagents that could be coupled to nucleosides to yield pure single ProTide isomers. From this study, phosphorochloridates with a pentafluorophenol were found to be optimal because the desired *Sp*-isomer phosphorochloridate was readily crystallized, stable, and allowed for the formation of the *Sp*-isomer ProTides, which is often the more active isomer.⁶⁵

Continuing on the theme of synthetic procedures with stereocontrol of the phosphorus chirality of the ProTides, researchers from Merck recently reported the discovery of a small molecule catalyst that, upon the addition to the reaction of a nucleoside with a phosphorochloridate, leads to the generation of a single isomer with significant preference for the 5'-hydroxyl compared to the 3'-one.⁶⁶ However, the reported catalyst generates the *Rp*-isomer and not the *Sp*-one, which often shows better pharmacological activity. This represents a challenge for the wide use of this catalyst. Impressively, more work from Merck researchers led to the identification of various Lewis acids as being able to improve the yield, stereoselectivity, and regioselectivity of the reaction of phosphorochlorides with nucleosides to generate ProTides.⁶⁷ Indeed, a selection of Lewis acids were studied and dimethyl aluminum chloride emerged as the optimal catalyst for this reaction.

In the synthesis of nucleoside monophosphate ProTides three different synthetic strategies are employed (Figure 5). The first strategy involves the *bis*-chlorination of a phosphate group to form a monophosphonate dichloridate. This is then followed by the addition of 1:1 mol equiv of the phenol and amino acid ester yielding the desired ProTides. Alternatively, in the second synthetic strategy, the monophosphonate group is initially coupled to one phenol group using *N,N*-dicyclohexylcarbodiimide (DCC) and the product is then chlorinated. Finally, the chloride group is substituted by the amino acid ester.

For the third synthetic strategy, the starting material employed is the diphenyl-masked nucleoside monophosphate, which first undergoes selective saponification that results in the removal of one of the phenyl masking groups. The product is subsequently coupled to the amino acid ester to

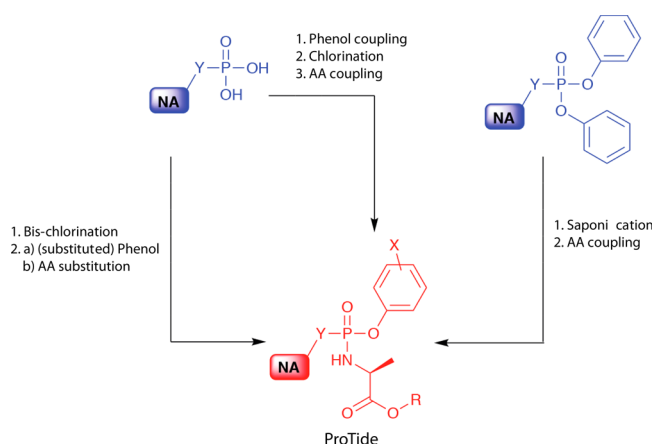


Figure 5. Synthetic strategies for accessing monophosphonate ProTides. AA: amino acid. NA: nucleoside analogue. R: any ester. X: any aromatic substitution. Y: O or CH₂.

generate the desired nucleoside analogue monophosphonate ProTide. Further details on the synthesis of the ProTides can be found in Pradere et al.²⁹ and Serpi et al.⁶⁸

4. METABOLISM OF THE PROTIDES

Once inside the cell, the ProTides require metabolism to release the nucleoside monophosphate. The metabolic conversion of the 2',3'-dideohydro-2',3'-dideoxythymidine (d4T)^{69–71} monophosphate (d4T-MP) ProTide to the eventual active metabolite d4T-TP has been extensively studied in several cell systems, including human lymphocytes (Figure 6). Beside efficient formation of d4T-MP, d4T-diphosphate (d4T-DP), and d4T-triphosphate (d4T-TP), an additional metabolite markedly accumulated upon exposure of the cell culture to the d4T-MP ProTide, which was identified as being the alaninyl d4T-MP. This metabolite may act as an intracellular depot form of d4T-MP, explaining not only the

superior antiviral activity of the ProTide versus the parental d4T but also the marked retainment of antiviral activity in thymidine kinase-deficient cells in which the parental d4T markedly loses antiviral efficacy.^{72,73} Also, the activation pathway of the ProTides of d4T-MP and AZT-MP containing different amino acids and/or ester moieties has been investigated. It was found that, overall, there was a close correlation between the anti-HIV activity of these prodrugs and their conversion rate to the amino acyl nucleotide metabolite (metabolite C, Figure 6).^{74,75} The metabolic conversion process is believed to be mediated by a two-step enzymatic process, which eventually releases the active monophosphate (or monophosphonate) form of the parent nucleoside as summarized in Figure 6.

The first step involves the cleavage of the amino acid ester by intracellular esterases. Researchers at Gilead Sciences identified cathepsin A as a major esterase that mediates the hydrolysis of ester motifs of ProTides.⁷⁶ Such finding has made cathepsin A widely used in the field in probing the hydrolysis of ProTides in vitro.^{64,77–79} Notably, a second enzyme that was able to hydrolyze the ester group of the two antiviral ProTides studied, TAF and 9-(R)-4-(R)-[[[(S)-1-[(ethoxycarbonyl)ethyl]-amino]phenoxy-phosphonyl]methoxy]-2-fluoro-1-furanyladenine (GS-9131)⁸⁰ (structure not disclosed), was also reported in this study but its identity was not determined.⁷⁶ In 2011, however, this identity of this second enzyme was established and was shown to be carboxylesterase 1 (CES1).⁸¹ Although both cathepsin A and CES1 were found to be expressed in primary hepatocytes, CES1 expression was undetectable in clone A replicon cells.⁸¹ This indicated that in primary human hepatocytes, both cathepsin A and CES1 are involved in the hydrolyzing of the carboxyl ester motif of the ProTides, whereas in clone A cells, cathepsin A is the major enzyme that mediates such process. Beyond cathepsin A and CES1, a series of cysteine and (lysosomal) serine proteases have also been identified as being able to hydrolyze the carboxyl ester motif of

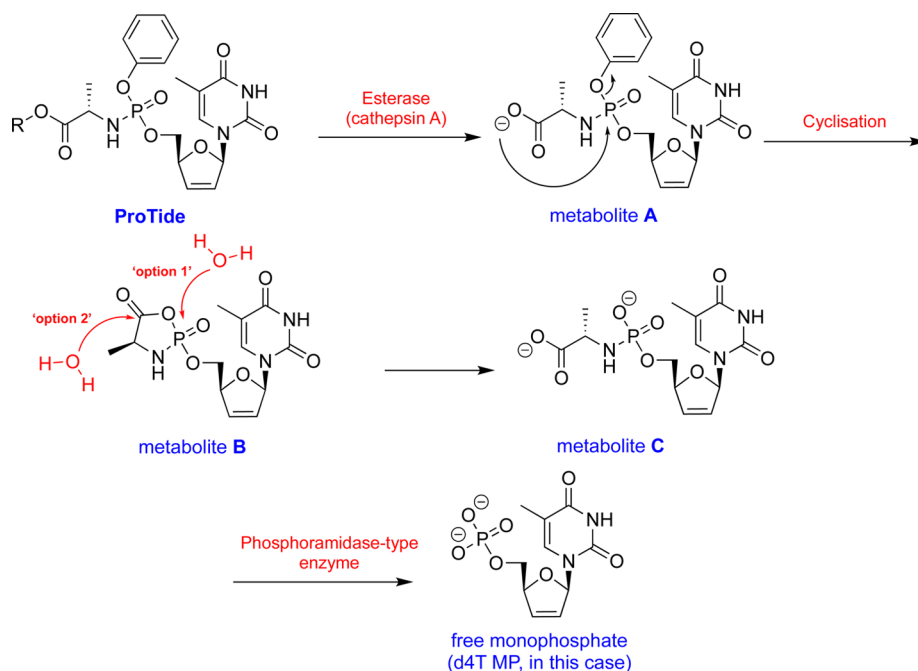


Figure 6. Postulated mechanism of ProTide metabolism illustrated using the ProTide of the anti-HIV agent d4T as an example.

the ProTides in quiescent cells and peripheral blood mononuclear cells (PBMC).⁸²

Earlier work by McGuigan and colleagues⁸³ into the efficiency of the ester group hydrolysis in various ProTides indicated that this is dependent on the structure of the ester moiety. In particular, it was noted that ProTides with a *tert*-butyl ester group were more slowly hydrolyzed than those bearing other esters, e.g., methyl, isopropyl, and benzyl, which correlated with the biological activity.⁸³ Although the lipophilicity of the ester motif seemed to give an increase in biological activity most likely due to increased cellular uptake, the rate of ester hydrolysis is another influencing factor in the ultimate biological activity of the ProTides.⁸³ For instance, ProTides with naphthyl esters yield more active ProTides than their phenyl ester counterparts due to higher lipophilicity and faster hydrolysis (Figure 7). However, propylbenzene esters, which are more lipophilic, are not as active as phenyl esters probably due to poor *in vivo* hydrolysis.

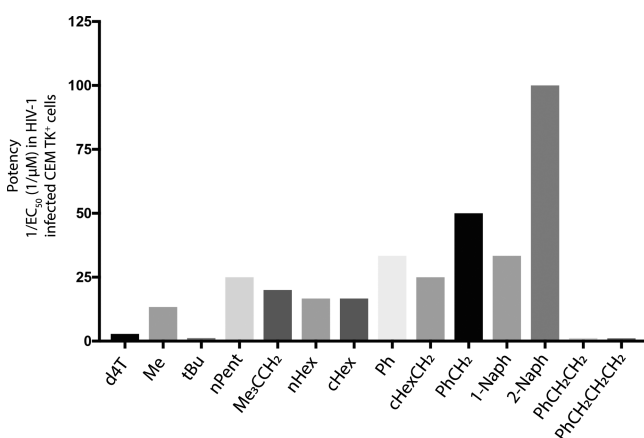


Figure 7. Effect of the ester motif on the ProTides' biological activity. The data presented regard d4T and its ProTides and were obtained from McGuigan et al.⁸³

In addition to the ester group's influence on the overall lipophilicity of the ProTides and its effect on the biological activity, the aryl motif has significant impact on the lipophilicity. In McGuigan's work, the aryl group mostly used was the phenyl group although the naphthyl group has also been explored. The biological activity between these two aryl motifs often correlated with lipophilicity, and hence the naphthyl-containing ProTides exhibit a better biological activity than their phenyl counterparts. Notably, substitutions on these aryl motifs exerts a significant impact on the biological activity (Figure 8). Electron-withdrawing substitutions were found to be associated with increased biological activity as compared to the electron-donating groups. The position on the aryl group that allows maximum electron-withdrawing effects, i.e., ortho and para, had more pronounced effects than the meta position.

Beyond the nature of the ester group, it has been shown that the nature of the amino acid of the ProTides also affects the rate of cathepsin A-mediated hydrolysis of the ester group (Figure 9).⁷⁶ Indeed, cathepsin A was unable to hydrolyze ProTides with branched amino acids such as valine and isoleucine. Subsequent studies showed that the nature of the amino acid side chain, primarily its size (bulkiness) and charge, has great influence on what enzyme hydrolyzes the ester motif.⁸² Indeed, an interesting structure–activity relationship

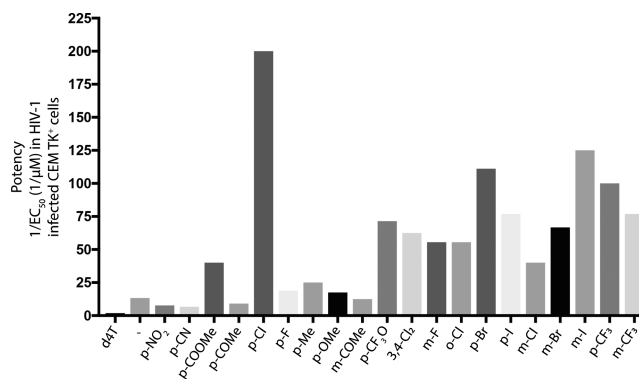


Figure 8. Effect of the aryl group substitutions on the ProTides' biological activity. The data presented regard d4T and its ProTides and were obtained from Siddiqui et al.⁸⁴

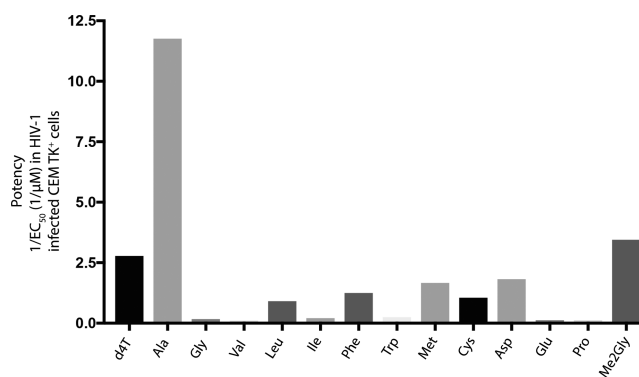


Figure 9. Effect of the amino acid on the ProTides' biological activity. The data presented regard d4T and its ProTides and were obtained from McGuigan et al.⁸⁵

emerged from the influence of the amino acid on the rate of the metabolism of ProTides. For instance, it was found that the ester motif of ProTides with alanine were efficiently processed by esterases (e.g., leukocyte elastase and proteinase 3) and serine proteases but not cysteine, aspartic, or metalloproteases.⁸² Amino acids with bulkier side chains, e.g., phenylalanine and leucine, were more efficiently hydrolyzed by chymotrypsin-related serine proteases such as cathepsin G and chymase.⁸²

After the ester motif at the amino acid moiety is cleaved off, a free carboxylate, which under physiological pH carries a negative charge, is generated. Subsequently, a nucleophilic attack by the carboxylate functionality on the phosphate or phosphonate group causes the loss of the aryl-leaving group, yielding a highly unstable five-membered anhydride ring. The speed of the nucleophilic attack from the carboxylate on the phosphate or phosphonate group varies depending on the nucleoside. For instance, AZT metabolite A formation (Figure 6) was slower than that of d4T.⁷⁵ Interestingly, the hydrolysis of ProTides with β -alanine did not release the nucleoside monophosphate because the hydrolysis did not proceed beyond the hydrolysis of the ester motif.⁷⁵ Metabolite B formation is followed by a rapid nucleophilic attack by a water molecule on the phosphate (option 1, Figure 6) or carbon of the carbonyl group of the amino acid (option 2, Figure 6) to open up the ring and to generate the phosphoramidate metabolite (metabolite C, Figure 6). Although no compelling evidence exists to whether the water molecule attacks the phosphate or the carbon of the carbonyl group of the amino acid, which both

yield the same product, the cleavage of the P–N bond at this stage has never been observed.⁸⁶

The final step in the metabolism of the ProTides is the cleavage of the P–N bond by a second enzyme known as a phosphoramidase-type enzyme (histidine triad nucleotide binding protein 1,⁸⁷ HINT1).^{81,88,89} This eventually leads to the release of the nucleoside monophosphate/phosphonate. Notably, the cleavage of the P–N bond can be resistant to HINT1 as is the case with TAF. It is hypothesized that the hydrolysis of the P–N bond in this case proceeds because of the chemical instability of the P–N bond in the acidic environment of endosomes/lysosomes.⁹⁰

5. PROTIDES IN DRUG DISCOVERY

Since the invention of the ProTide technology by the McGuigan laboratory in the early 1990s, this modality has been widely employed in the synthesis of many nucleoside monophosphate or monophosphonate ProTides. Although initially the structure–activity relationship (SAR) studies were performed on pyrimidine nucleosides such as AZT and d4T, a wide variety of other ProTide derivatives have also been synthesized and antivirally evaluated. Notably, application of the phosphoramidate ProTide technology on purine nucleoside analogues such as 2',3'-dideoxyadenosine (ddA) and 2',3'-dideohydro-2',3'-dideoxyadenosine (D4A),⁹¹ carbocyclic adenosine derivatives,⁹² and carbovir/abacavir^{93,94} often led to markedly enhanced antiviral potencies of such ProTides. More recently, it was even shown that ProTides of the antiherpetic acyclovir resulted in both antiherpetic and anti-HIV activity^{95,96} and thus, enabled broadening of the antiviral spectrum of such drug. In this respect, it should be mentioned that the ProTide technology not only enables significant optimization of existing antiviral drugs, but it also allows conversion of apparently looking inactive molecules to active antivirals by the improved uptake and direct delivery of their activated (monophosphate) species. A series of ProTides have reached clinical trials,⁵³ with two of them already approved for clinical use.¹³ To highlight the usefulness of this prodrug technology in drug discovery, key ProTides that are currently reported to be undergoing clinical trials and those that have received FDA-approval will be discussed.

5.1. ProTides as Clinical Candidates. **5.1.1. Benzyl (((2R,3R,5R)-5-(4-Amino-2-oxopyrimidin-1(2H)-yl)-4,4-difluoro-3-hydroxytetrahydrofuran-2-yl)methoxy)(phenoxy)phosphoryl)-L-alaninate (NUC-1031).** NUC-1031 (**1**, Figure 10)⁶⁴ is a phenyl L-alanine benzyl ester ProTide of the FDA-approved anticancer nucleoside analogue gemcitabine (Gemzar)⁹⁷ and developed for clinical use by NuCana Biomed Ltd. Gemcitabine emerged as an ideal candidate for the application of the ProTide technology because of the emerging resistance against this anticancer therapeutic agent. Gemcitabine resistance mechanisms include inadequate conversion of gemcitabine into its pharmacologically active di- and triphosphate forms due to downregulation of deoxycytidine kinase, deamination of gemcitabine to its much less active uridine derivative, and mutations in the membrane transporter that mediates its active uptake into cells.⁹⁸

A series of gemcitabine ProTides were synthesized and probed for their cytostatic activities.⁶⁴ The lead structure from these studies was **1** as it exhibited significant antiproliferative activity, superior in vivo stability, and an excellent PK profile.⁶⁴

A notable result that emerged from the ProTide was that it was able to effectively overcome gemcitabine resistance. This

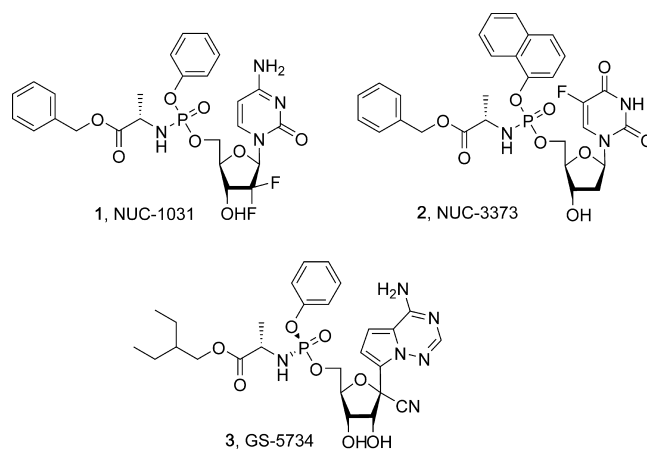


Figure 10. Chemical structures of key ProTides undergoing clinical trials.

was attributed to three main reasons: first, cytidine deaminase is an enzyme found in both serum and cells and is known to catabolize gemcitabine. For deamination to occur, unprotected hydroxyl groups on the 3'- and 5'-position of the nucleoside analogue must be present.⁹⁹ ProTide **1** demonstrated resistance to deamination because of the presence of the phosphoramidate moiety on the 5'-O-position of the ribose moiety. A second advantage of being resistant to deaminase breakdown is an increased safety profile, as lesser toxic metabolite (2',2'-difluorodeoxyuridine) would be produced.⁶⁴ Second, it was found that the cellular uptake of **1** was not dependent upon nucleoside transporters and that the ProTide was lipophilic enough to enter the cells via passive diffusion. This was deduced following an experiment involving dipyridamole, a known inhibitor of the human equilibrative nucleoside transporter 1 (hENT1), to mimic the downregulation of nucleoside transport in cancer cells. Gemcitabine was incubated with pancreatic PANC1 cancer cells in the presence of dipyridamole, and it was found that its cytotoxic activity was significantly reduced, with the cytostatic activity decreasing from 611 nM to >2000 nM (CC₅₀). Contrastingly, even with blockage of hENT1, the activity of **1** remained fairly constant (CC₅₀ = 162 μM), thus confirming that the cellular uptake of **1** is independent of nucleoside transporters.⁶⁴ Third, the structure of the ProTide is such that it is able to overcome the rate-limiting first phosphorylation-mediated by deoxycytidine kinase which is downregulated in certain cancers. This was confirmed by little change in the activity of **1** when incubated with RT112 cancer cells in the presence of 2'-deoxycytidine being the competing natural substrate for gemcitabine activation to its 5'-monophosphate by 2'-deoxycytidine kinase (EC₅₀ = 0.7 μM in the presence of 2'-deoxycytidine compared to 0.2 μM in the dCyd absence). Conversely, the activity of gemcitabine decreased when 2'-deoxycytidine was coadministered as the two compounds competed for the same active site on the deoxycytidine kinase.⁶⁴

In vivo animal studies of compound **1** were conducted, focusing in particular on gemcitabine (partially) resistant pancreatic cancers. The initial results obtained were very promising. In mouse models with human tumor xenografts, **1** reduced the tumor size faster than gemcitabine, and significant reductions in tumor size were noticeable on day 7 post administration of the ProTide. The body weight of the animals was also recorded to assess their tolerance to the compound.

Overall, ProTide **1** was associated with less than 4% reduction in body weight and it was found that over the course of the treatment, the mean body weight change was less pronounced in mice that were treated with **1** compared to those treated with gemcitabine. This indicated that the gemcitabine ProTide was better tolerated than the parent nucleoside analogue.⁶⁴ The pharmacokinetics of the ProTide were also considerably better than those of gemcitabine: the half-life of **1** was 7.9 h compared to 1.5 h for gemcitabine. The ProTide also led to intracellular concentrations of the active gemcitabine triphosphate metabolite that was 13 times higher than achieved by gemcitabine.¹⁰⁰

Phase I/II clinical trials were conducted involving 68 patients and showed that **1** was effective in a variety of different cancers but most notably in patients with ovarian, pancreatic, and biliary cancers. Phase III studies will be conducted focusing on these cancers in particular. The ProTide was found to be stable in vivo, exhibiting a plasma half-life of 8.3 h. Maximum intracellular concentrations of the active metabolite were quickly achieved, peaked at 475 μM , and were maintained for 24 h. In several patients, the tumor had shrunk by more than 30%, whereas in 33 patients, the disease had stabilized.¹⁰¹

5.1.2. Benzyl (((2*R*,3*S*,5*R*)-5-(5-fluoro-2,4-dioxo-3,4-dihydropyrimidin-1(2*H*)-yl)-3-hydroxytetrahydrofuran-2-yl)-methoxy)(naphthalen-1-yloxy)phosphoryl)-L-alanine (NUC-3373). Another ProTide currently being developed for clinical use by NuCana Biomed Ltd. is NUC-3373 (**2**, Figure 10),^{79,102} a phosphoramidate prodrug of 5-fluoro-2'-deoxyuridine (FdU). FdU is a metabolite which gets formed in vivo from the pharmacologically active anticancer agent 5-fluorouracil (5-FU). Initially discovered by McGuigan and his colleagues in 2011 after extensive SAR studies,⁷⁹ ProTide **2** displayed promising preclinical results and initial studies highlighted its superiority over its parent nucleoside, 5-FU. The path toward the final structure of **2** began with McGuigan and his co-workers by synthesizing and comparing 39 different ProTides, with variations in the aryl, ester, and amino acid regions.⁷⁹ There was little difference observed in the potency of the ProTides upon varying the amino acid ester region and also upon changing the nature of the amino acid. L-Alanine has long been the amino acid of choice when formulating ProTides, but there was little to discern between L-alanine and the other amino acids in these experiments. Generally, the ProTides yielding the 1-naphthyl group displayed more potency than phenyl-containing ProTides, thus leading to the deduction that the 1-naphthyl, benzyl ester-containing ProTide was the most effective.⁷⁹ To determine the cytotoxic activity of **2**, in vitro studies were conducted involving human tumor cell lines (colorectal, lung, ovarian, acute lymphoblastic leukemia, and cervix). Attention to thymidine kinase and the nucleoside transporter hENT1 was also given to investigate the characteristics of cancer resistance. Xenograft mouse models were also used to further analyze the anticancer activity of the ProTide.¹⁰³

It was found that compound **2** was, on the whole, significantly more cytotoxic than 5-FU, displaying IC_{50} values 2–333-times lower in the majority of the tumor cell lines tested. The ProTide also produced 363-times more of the active metabolite (FdU) than 5-FU, thus further displaying its superiority in efficacy. Thymidine kinase inhibition only slightly affected ProTide **2** (~4-fold) compared to FdU that showed reductions in cytotoxicity of up to 136-fold, respectively, indicating the independence of the ProTide for the FdU-activating enzyme. Significant results were obtained with the colorectal tumor xenografts: ProTide **2** inhibited tumor growth

by 47% compared to 25% tumor growth inhibition demonstrated by 5-FU.¹⁰³

Compound **2** was found to overcome the main mechanisms of resistance that is associated with 5-FU and other drugs within this family, such as decreased levels of the necessary phosphorylating (activating) enzyme thymidine kinase, which is required to produce the active metabolite; an overexpression of thymidylate synthase (an enzyme responsible for DNA synthesis and a target for FdUMP (the active metabolite of 5-FU) altered levels of thymidine phosphorylase and reduced entry into the cells via nucleoside transporters.^{79,102} ProTide **2** overcomes these pathways to resistance by preventing degradation by phosphorolytic enzymes, bypassing the need to be activated by thymidine kinase, and being able to diffuse into cells, independent of nucleoside transporters such as hENT1.¹⁰⁴ Given the encouraging results obtained in the preclinical studies, ProTide **2** entered phase I clinical trials in the first quarter of 2016 in pursuance of determining the pharmacokinetic profile of the ProTide, the safety of the compound in human participants and clinical activity of **2** in tumor-bearing patients.¹⁰³ The trial itself consists of two parts: the first part assessing the optimum dose that will maximize the risk/benefit reward to the participants when given a weekly dose of the ProTide, administered as a single intravenous infusion. The second part will assess the same as part one, except the dosing interval which will be increased to fortnightly (www.clinicaltrials.gov, trial identifier: NCT02723240).

5.1.3. 2-Ethylbutyl ((S)-(((2*R*,3*S*,4*R*,5*R*)-5-(4-Aminopyrrolo[2,1-*f*][1,2,4]triazin-7-yl)-5-cyano-3,4-dihydroxytetrahydrofuran-2-yl)methoxy)(phenoxy)phosphoryl)-L-alanine (GS-5734). In 2014, there was a mass outbreak of the Ebola virus, most prevalent in Western Africa, although there were a number of reported cases in the USA and the United Kingdom. In West Africa alone, there were a total of 28616 confirmed cases in Guinea, Liberia, and Sierra Leone, leading to 11310 deaths (WHO 2016). To this date, there is no drug treatment available on the market to treat this disease. However, GS-5734 (**3**, Figure 10),¹⁰⁵ developed by Gilead Sciences, has shown promising results as a potential treatment for the Ebola virus. Although most of the interest in this compound has been due to its activity against Ebola, recently, **3** was reported to be a broad-spectrum antiviral agent because it exhibited potent antiviral activity against a variety of viruses including filoviruses, coronaviruses, and paramyxoviruses.¹⁰⁶

Compound **3** is a ProTide of an adenosine analogue which, following intracellular delivery, gets metabolized into the pharmacologically active nucleoside triphosphate form, which then inhibits viral RNA dependent RNA polymerase.¹⁰⁵

The activity of **3** was initially tested using cell-based assays, followed by the administration of the ProTide to rhesus monkeys that were infected with the Ebola virus. Rodent studies were deemed not suitable to determine the pharmacokinetics of **3** due to the high serum concentrations of esterases present in many rodent species, which would prematurely degrade the ProTide and impact on the findings. Thus, rhesus monkeys were chosen as they closely resemble humans and they do not express a high serum esterase concentration.¹⁰⁵ Then 10 μM **3** was incubated in a 2 h pulse or 72 h continuous incubation of Ebola virus-infected human primary macrophages, endothelial cells, and liver cells to deduce its activity. Then 10 μM nucleoside analogue was also incubated for 72 h in human monocyte-derived macrophages for comparison. ProTide **3** was found to be rapidly metabolized

in the primary macrophages, with maximum intracellular concentrations of nucleoside triphosphate being achieved after 4 h post incubation, with a half-life of 16 h. It was found that **3** displayed an EC_{50} value against Ebola virus of $0.086 \mu\text{M}$ in the human primary macrophages, $0.14 \mu\text{M}$ in the endothelial cells, and $0.07 \mu\text{M}$ in the Huh-7 liver cells. In comparison, the nucleoside analogue displayed an EC_{50} value of greater than $20 \mu\text{M}$ in both the human macrophages and endothelial cells, and $1.5 \mu\text{M}$ in the liver cells. The cytotoxic concentration (CC_{50}) of the ProTide in all cell lines was above $20 \mu\text{M}$. The different cell lines were also infected with different variants of the Ebola virus (Makona and Kikwit variants) and other filoviruses. The cell-based assays gave strong indication that compound **3** would be effective in treating the other viruses as well.¹⁰⁵

The pharmacokinetics of **3** were examined in rhesus monkeys. After being administered intravenously with 10 mg/kg of the ProTide, **3** displayed a very short plasma half-life of just 0.39 h . There was rapid distribution into the peripheral compartments within 2 h post administration, and a half-life in the peripheral blood mononuclear cells of 14 h was observed. Levels required to achieve a 50% inhibition of the Ebola virus were maintained for 24 h .¹⁰⁵ Compiling the pharmacokinetics results and tissue distribution data led to the conclusion that once daily dosing would be effective to achieve a clinical effect.

To assess the efficacy of the ProTide, a blinded placebo-controlled study was conducted involving 12 Ebola-infected rhesus monkeys (six per treatment group) in two different modalities.¹⁰⁵ The first part involved intramuscular administration of **3** either on day 0 (same day as being infected with Ebola), or day 2. Part two of the study administered a loading dose of 10 mg/kg followed by once daily doses of 3 mg/kg , commencing at various days after virus exposure or 10 mg/kg administered on day 3 post virus exposure. All of the monkeys given **3** survived until the end of the trial; 50% survival was noted with the treated group of animals given 3 mg/kg compared to no survival in the placebo group. It was noted that monkeys given the 10 mg/kg dose after day 3 had 100% survival along with reduced signs associated with the Ebola virus (thrombocytopenia, coagulopathy).¹⁰⁵

Given the promising results obtained in the rhesus monkey study, a phase II clinical trial is due to be conducted in Liberia. Sponsored by the National Institute of Allergy and Infectious Diseases, 60–120 men infected with Ebola virus will be recruited and will be given a five-day course of **3**, administered once daily, followed by monitoring over a six-month period to determine the clearance of virus from a persistent genital reservoir (www.clinicaltrials.gov, trial identifier: NCT02818582).

5.2. ProTides as Drugs. There have been two ProTide drugs approved by the FDA for clinical use. Sofosbuvir (Sovaldi), Figure 3, was approved by the FDA in December 2013 for the treatment of HCV.¹⁰⁷ Sofosbuvir is a phosphoramidate prodrug of 2'-deoxy-2'-fluoro-2'-C-methyluridine, the parent nucleoside. Having emerged as the superior ProTide out of 50 other ProTides developed,³⁵ sofosbuvir was acquired by Gilead Sciences, where it adopted the identity sofosbuvir and underwent further extensive clinical evaluation. Sofosbuvir was found to act by inhibiting the HCV NSSB polymerase, an enzyme responsible for the replication of the viral genome. Inhibition of this enzyme would result in RNA chain termination and ultimately stop the replication of HCV.³⁵ Following cellular uptake by hepatocytes, sofosbuvir undergoes

sequential hydrolysis by cathepsin A and CES1 to form the active nucleoside monophosphate. Further hydrolysis by HINT1 and subsequent phosphorylations yielded the pharmacologically active triphosphate metabolite, which exerts its action on NSSB polymerase.¹⁰⁸ Initial animal studies of sofosbuvir were encouraging. The ProTide was well absorbed following oral administration in portal vein cannulated dogs, bioavailability was 9.9%, which equated to a fraction absorbed of 36%.¹⁰⁹ In human subjects, the absolute bioavailability was not determined, although over 80% of the administered dose was absorbed. The absorption was rapid, with maximum concentrations (C_{max}) of sofosbuvir achieved $0.5\text{--}2 \text{ h}$ post oral administration and C_{max} of the inactive parent nucleoside metabolite was achieved $2\text{--}4 \text{ h}$ post administration and a half-life of $0.48\text{--}0.75 \text{ h}$. Ex vivo studies of the distribution of the anti-HCV agent showed a plasma protein binding of around 82% in healthy subjects and 85% in subjects with end stage renal disease.¹⁰⁸

Studies using the diastereomeric mixture of sofosbuvir in humans showed that it was rapidly absorbed and metabolized in the liver according to the typical in vivo degradation of the ProTides (see Figure 6). Briefly, the isopropyl ester motif was hydrolyzed into the naked carboxylate group and then the P–N bond of the phosphoramidate group was cleaved off to afford parent nucleoside monophosphate.¹¹⁰ Notably, the parent nucleoside, an inactive metabolite, was detectable in the plasma and remained detectable for at least 24 h following the 100 and 800 mg dosing of the diastereomeric mixture of sofosbuvir.¹¹⁰ Although sofosbuvir showed little indication of being excreted renally (3.5% recovered in urine; renal clearance = 0.238 L/min), the inactive parent nucleoside was the predominant compound present in the urine (77.7%), indicating excretion via the kidneys. This was further confirmed when studies were conducted by observing the pharmacokinetics of sofosbuvir in patients with impaired renal function; the renal clearance of the parent nucleoside was around 2-fold higher than the glomerular filtration rate, signifying active renal excretion of the metabolites of sofosbuvir.¹⁰⁹ Phase II studies of sofosbuvir in combination with pegylated interferon and ribavirin established the doses required to provide an optimal effect while minimizing any potential adverse effects.¹¹¹ Initial studies postulated that 200 mg or 400 mg doses of sofosbuvir with pegylated interferon and ribavirin were most effective, as 100 mg dosing was found to be suboptimal due to low viral load decline than observed with the 200 mg and 400 mg doses. At these doses, the incidence of adverse effects was low, with the most frequent adverse effects being fatigue and nausea.¹¹¹ Coupled with the short half-life of sofosbuvir, once daily dosing was recommended as there was little accumulation of the drug.¹⁰⁹

The safety of sofosbuvir was later confirmed in phase II clinical trials. It was postulated that as sofosbuvir is not metabolized via the cytochrome P450–3A4 enzymes, drug–drug interactions would be minimal. However, because it seems to induce the P-glycoprotein efflux pump, caution was advised with coadministration of carbazepine and rifabutin as the concentrations of sofosbuvir can decrease significantly.^{112,113}

Single-group, open label phase III study of treatment-naïve patients with HCV genotypes 1, 4, 5, and 6 treated with sofosbuvir plus pegylated interferon and ribavirin for 12 weeks indicated high potency of sofosbuvir.¹⁰⁷ Indeed, 80% of cirrhotic patients versus 92% of noncirrhotic patients achieved a viral load below the lower limit of quantifications 12 weeks

after completion of HCV treatment (SVR12). This indicated the efficacy of sofosbuvir in treating different HCV genotypes, confirming similar earlier preclinical observations.¹¹⁴ In a placebo-controlled phase III study comparing sofosbuvir and ribavirin for 12 weeks with matched interferon ineligible controls in genotype 2 and 3 patients, sustained viral response was achieved in 78% of treated patients with 93% response rate in genotype 2 patients and 61% in genotype 3 patients.¹¹⁵ In a study involving patients who had previously been treated with interferon who were treated with either sofosbuvir and ribavirin for 12 weeks followed by placebo for 4 weeks or sofosbuvir and ribavirin for 16 weeks, response rates showed a 73% SVR12 in the 16-week arm compared to 50% of the 12-week arm. Impressively, 94% of genotype 2 patients achieved SVR12 within 12 weeks of treatment with sofosbuvir and ribavirin, while 87% achieved it within 16 weeks. As for genotype 3 patients, 30% of patients achieved SVR12 within 12 weeks compared to 62% within 16 weeks. Notably, 46% of the patients treated with sofosbuvir and ribavirin for 12 weeks had viral relapse compared to 27% of the 16-week treatment arm. In another study, the efficacy of extended treatment of 24 weeks of sofosbuvir plus ribavirin in genotype 3 patients was evaluated.¹¹⁶ The results showed that 93% of the 73 patients with genotype 2 who took part achieved SVR12 within 12 weeks of sofosbuvir and ribavirin treatment, whereas 85% of the 250 patients with genotype 3 treated for 24 weeks with sofosbuvir and ribavirin achieved SVR12. This was the first large scale study showing the efficacy of prolonged interferon-free treatments in genotype 3 patients. Given the excellent safety profile and pan-genotypic efficacy of sofosbuvir, it has been licensed for clinical use in combination with pegylated interferon, ribavirin, and the NSSA inhibitors ledipasvir and velpatasvir depending on the HCV genotype to be treated.¹¹⁷ Collectively, this has made sofosbuvir a cornerstone in HCV therapy.

TAF, Figure 3, is the latest ProTide-based drug approved by the FDA for the treatment of HIV.¹¹⁸ Developed by Gilead Sciences Inc., TAF is a ProTide of the acyclic nucleoside phosphonate drug tenofovir. Another prodrug of tenofovir, tenofovir disoproxil fumarate (TDF), had long been an FDA-approved treatment for HIV, however, the ProTide TAF demonstrated increased anti-HIV activity, higher in vivo stability, and was endowed with fewer side effects than both tenofovir and TDF.¹¹⁸ TAF is specifically accumulating in lymphatic tissue, and in the liver, and thus, holds also great potential for the treatment of HBV infections. Markedly lower plasma levels but significantly higher intracellular tenofovir concentrations are observed with TAF as compared to TDF, explaining the lower incidence of tenofovir-associated side effects with respect to bone mineral density losses and kidney nephrotoxicity.¹¹⁹ The drug itself becomes phosphorylated following cellular uptake into the pharmacologically active diphosphate form and is a potent inhibitor of reverse transcriptase. Inhibition of this enzyme results in DNA chain termination and viral replication ceases to progress.¹²⁰

Early studies of TAF were conducted in dogs in order to characterize its pharmacokinetic profile and understand its permeability and efficacy as a potential treatment for HIV. Initial in vitro studies using hepatic and intestinal S9 fractions from both humans and dogs yielded similar results, highlighting the suitability of using dogs for the preclinical studies. In vitro experiments showed TAF to have half-lives of 31 min in both dog intestinal and hepatic S9 fractions, a plasma half-life of 92

min, and a half-life of 28.3 min in an MT-2 cell extract.⁸⁰ When 5 mg/kg of TAF were administered to the dogs, plasma concentrations peaked at 1.58 μM , achieved at 0.14 h post administration. The levels of TAF decreased rapidly (undetectable after 2 h post administration), which was accompanied by an increase in tenofovir levels. Rapid accumulation of the active metabolite tenofovir diphosphate in the peripheral blood mononuclear cells followed, with peak concentrations of 18 μM achieved at 1 h post administration. The bioavailability of TAF was found to be dependent on the administered dose, with bioavailabilities of 1.7% and 24.7% at 2 and 20 mg/kg, respectively.¹²¹ However, other studies found that oral administration of 10 mg/kg of TAF yielded a bioavailability of 17% when compared to the intravenous dose,⁸⁰ with the majority of the drug metabolized in the kidneys and excreted in the urine.¹²²

An earlier study conducted by Eisenberg et al. in 2001¹²³ compared the activity of the ProTide with tenofovir and its prodrug TDF. Following incubation with peripheral blood mononuclear cells, it was found that the levels of tenofovir and its metabolites were 10–30 times higher compared to TDF and tenofovir, respectively.¹²³ The in vitro anti-HIV activity of TAF was determined to be 1000-fold and 10-fold greater than tenofovir and TDF.⁸⁰

Following successful in vitro assessments of TAF, the ProTide progressed into a number of phase I and II trials, where the in vivo pharmacokinetics/dynamics of the ProTide was evaluated and compared to its predecessors along with establishing the optimum dose of TAF. An initial study was conducted by Markowitz et al.,¹²⁴ where either 40 or 120 mg of TAF or 300 mg of TDF were administered once daily for 14 days and the activity of both prodrugs as monotherapy for the HIV-1 infection was compared. The study showed that both 40 mg and 120 mg of TAF resulted in higher intracellular concentrations of tenofovir diphosphate in PBMC than tenofovir. TAF also produced a greater net change in HIV-1 RNA compared to TDF, thus illustrating its superiority over the existing prodrug in terms of potency.¹²⁴

Phase II/III studies of TAF focused on its efficacy in different patient groups including, but not limited to, adults and adolescents. As tenofovir is eliminated via the kidneys, it was imperative to understand how renal function would affect both the accumulation of tenofovir in the body and also its excretion. TDF has been associated with effects on the bone and renal toxicity, leading to decreased glomerular filtration rates, increases in serum creatinine, and increased risk of adverse renal events. This toxicity was attributed to its effect in the proximal tubule, with efficient uptake from plasma but less efficient efflux into urine resulting in accumulation of tenofovir in the body.¹²⁵ Therefore, a phase 3 double-blinded study was conducted in which TAF was administered to patients with impaired renal function. Patients were given either 10 mg of TAF or 300 mg of TDF, each coformulated with elvitegravir, cobicistat, and emtricitabine. The study found that participants on the TAF treatment regime displayed a smaller increase in creatinine, less proteinuria, and significant decreases in bone mineral density.¹²⁶

TAF was demonstrated to be superior not only in its antiviral activity but also in the fact that therapeutic effects could be achieved at much lower doses than TDF, thus reducing the incidence of adverse effects. This led to the FDA approval of the ProTide in the treatment of HIV-1 in a combination therapy with other anti-HIV agents.¹¹⁸ Moreover, in November

2016, the FDA granted approval for a once-daily treatment of 25 mg TAF in patients suffering from chronic HBV infection (Gilead Sciences 2016). This followed extensive studies which highlighted the ProTides superiority over current therapies used to treat not only HIV but also chronic HBV infections.¹²⁷

6. CONCLUSIONS AND OUTLOOK

The ProTide technology has facilitated the discovery and application of a variety of nucleoside monophosphate and monophosphonate analogues in the clinic. It took many years of trial and error, mainly by the McGuigan group, to optimize the masking groups of the phosphate to yield the successful ProTide technology as we know it today. Although this technology has largely been used in the discovery of nucleoside-based ProTides as antiviral and anticancer agents, recently it was applied in the early discovery of nucleoside-based ProTides for Parkinson's disease.⁷⁸ Additionally, the ProTide prodrug approach is receiving increasing attention as a prodrug strategy for the intracellular delivery on monophosphorylated non-nucleoside compounds such as glucosamine,^{128,129} Sphingosine 1-phosphate (S1P),¹³⁰ 4-phospho-D-erythronhydroxamic acid,¹³¹ and 5-phospho erythronhydroxamic acid.¹³² Together, these examples show the broad usefulness of this prodrug technology and highlight its potential in the discovery of non-nucleoside monophosphate and monophosphonate prodrugs as potential therapeutics as well. Regardless of the substrates to which the ProTide technology is applied to either nucleosides or non-nucleosides, it has already proven to be a powerful technology in drug discovery and efficient intracellular delivery of the (activated) parental drug. Given its expanding applications, there is a real possibility that this technology will deliver new (nucleoside and non-nucleoside) ProTides for the treatment of a variety of other diseases beyond microbial infections and cancer.

AUTHOR INFORMATION

Corresponding Authors

*For Y.M.: phone, +44 (0) 2920875821; E-mail, MehellouY1@cardiff.ac.uk.

*For J.B.: phone, +32 (0) 494288861; E-mail, jan.balzarini@kuleuven.be.

ORCID

Youcef Mehellou: [0000-0001-5720-8513](https://orcid.org/0000-0001-5720-8513)

Notes

The authors declare no competing financial interest.

Biographies

Youcef Mehellou obtained his M.Pharm. (Pharmacy) degree from King's College London in 2005. This was followed by a Ph.D. on "ProTide" chemistry under the supervision of Prof. Chris McGuigan at Cardiff University, U.K. Following postdoctoral work initially with Prof. Sidney M. Hecht at Arizona State University (2009/2010) and then with Prof. Dario R. Alessi FRS at the University of Dundee, U.K. (2010/2013), Youcef moved to the University of Birmingham, U.K., in early 2013 as a Lecturer in Medicinal Chemistry. Since January 2017, Youcef has been a Lecturer in Medicinal Chemistry in Cardiff University, U.K., where his group is focusing on the discovery of small molecule modulators of signal transduction and the development of novel phosphate and phosphonate prodrug therapeutics.

Hardeep S. Rattan is currently a fourth and final year Pharmacy student at the University of Birmingham, U.K. He has a keen interest in medicinal chemistry, particularly the discovery and development of

nucleoside and nucleotide therapeutics. Hardeep's final year Masters research project focused on the ProTide prodrug technology and was carried out under the supervision of Dr. Mehellou.

Jan Balzarini graduated from the KU Leuven (Belgium) as Master in Biology (1975), Master in Bioengineering (1977), and Ph.D. in Bioengineering (1984). He is affiliated to the Rega Institute for Medical Research at the KU Leuven. In 1984, he became tenured and performed a postdoctoral stay at the National Cancer Institute of the NIH (1985/1986) with Sam Broder and David G. Johns. In 2001, he was awarded the prestigious René Descartes Research Prize of the European Commission (in collaboration with several European Research Teams), and he received several other (inter)national awards. In 2001, he became full professor at the KU Leuven; in 2006, he was appointed as Laboratory Head of Virology and Chemotherapy at the Rega Institute, and in 2014, he retired as Emeritus Professor.

DEDICATION

This review was written in memory of Prof. Christopher McGuigan (1958–2016), who provided the basis for the ProTide technology.

ABBREVIATIONS USED

5-FU, 5-fluorouracil; AraA, 9- β -D-arabinofuranosyladenine; AraC, 1- β -D-arabinofuranosylcytosine; AZT, 3'-azidothymidine; d4A, 2',3'-didehydro-2',3'-dideoxyadenosine; CES1, carboxylesterase 1; d4T, 2',3'-didehydro-2',3'-dideoxythymidine; ddC, 2',3'-dideoxyadenosine; ddC, 2',3'-dideoxycytidine; DCC, N,N'-dicyclohexylcarbodiimide; FDA, Food and Drug Administration; FdU, 5-fluoro-2'-deoxyuridine; FdUMP, 5-fluoro-2'-deoxyuridine-5'-monophosphate; HBV, hepatitis B virus; HCMV, human cytomegalovirus; HCV, hepatitis C virus; hENT1, human equilibrative nucleoside transporter 1; HINT1, histidine triad nucleotide-binding protein 1; HIV, human immunodeficiency virus; HSV, herpes simplex virus; NA, nucleoside analogue; NMI, N-methylimidazole; PK, pharmacokinetics; SVR12, the lower limit of quantifications 12 weeks after completion of HCV treatment; TAF, tenofovir alafenamide; TDF, tenofovir disoproxil fumarate; SAR, structure–activity relationship; tBuMgCl, *tert*-butyl magnesium chloride; TK, thymidine kinase

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