

A new class of NO-donor pro-drugs triggered by γ -glutamyl transpeptidase with potential for reno-selective vasodilatation†

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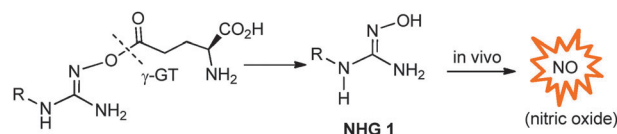
This communication describes the synthesis of a new class of *N*-hydroxyguanidine (NHG) pro-drugs which release nitric oxide (NO), triggered by the action of γ -glutamyl transpeptidase (γ -GT), and have potential for the treatment of acute renal injury/failure (ARI/ARF).

Acute renal injury (AKI), or failure (ARF), is a common complication that affects millions of people worldwide, particularly in intensive care units, where it is associated with a mortality rate of between 50% and 80%.¹ There is no effective pharmaceutical therapy to date. One of the major causes of AKI is ischemia-reperfusion injury,^{2,3} following aortic ring cross-clamping during by-pass surgery, which can lead to renal ischemia.⁴ Reperfusion of ischemic renal tissue causes the generation of reactive oxygen species which induce renal cell injury⁵ and promote impairment of renal perfusion at least in part *via* inactivation of the vasodilator, nitric oxide (NO).^{6–8} Thus, a kidney selective vasodilator with antioxidant properties is attractive to maintain blood flow to offset AKI and scavenge the reactive oxygen species. Localisation of activity to the kidney would avoid a systemic reduction in blood pressure. Dopamine and fenoldopam, specific agonists of the dopamine-1 receptor, have been used clinically in an effort to reduce the risk of perioperative renal dysfunction, but the effectiveness of these agents is not clear.^{9,10} We hypothesised that an effective exogenous NO-donor, which selectively increases renal vasodilatation, would offer an alternative.

There are a wide range of NO-donor drugs in existence,¹¹ including conventional organic nitrates and nitrites, *S*-nitrothiols, NONOates and *N*-hydroxyguanidines (NHGs).^{12–16} The NHGs **1** are analogues of *N*^o-hydroxy-L-arginine (NOHA), a biosynthetic intermediate involved in the generation of NO from L-arginine.¹¹ Several enzymatically activated NHG pro-drugs have been reported such as peptidylglycine α -amidating monooxygenase (PAM)-active *O*-carboxymethyl *N*-hydroxyguanidines¹⁷ and *N*- β -galactosidases-active (β -D-galactopyranos-1-yl)oxyguanidine.¹⁸ Our approach aimed to mask the NO generating *N*-OH group with a γ -glutamyl residue to facilitate activation by the enzyme, γ -glutamyl transpeptidase (γ -GT). Given that γ -GT is primarily expressed in the kidney (5–10 fold higher than in the liver and pancreas),¹⁹ it was envisaged that this enzyme could be used to trigger reno-selective release of an NHG and subsequent *in situ* generation of NO (Scheme 1). A similar strategy has been described for reno-selective L-3,4-dihydroxyphenylalanine (L-DOPA), the Glu-DOPA.^{20,21}

However, the direct coupling of NHGs with a γ -glutamyl residue was hampered by intramolecular cyclization and dehydration leading to a 1,2,4-oxadiazole ring; or alternatively lactamization and release of a pyroglutamic acid (Scheme 2, data not included).

In an effort to prevent these modes of cyclization, we investigated the use of a bridge between the NHG and the γ -glutamyl group. Both γ -glutamyl itself and γ -aminobutanoyl (GABA)²² were explored as linkers. Thus **2a** and **2b** became synthesis targets (Scheme 3) and they were prepared *via* appropriately protected dipeptide intermediates (ESI;† Scheme S1). Unfortunately **2a** gradually decomposed presumably due to the carboxylic acid moieties promoting autodegradation.

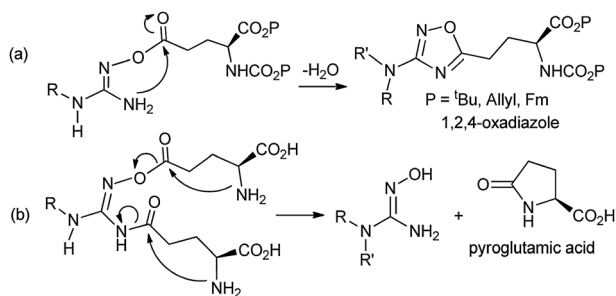


Scheme 1 Approach to γ -GT triggered release of NHG **1** and the reno-selective release of nitric oxide.

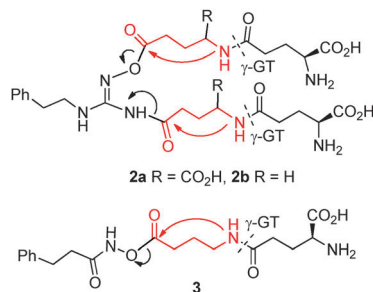
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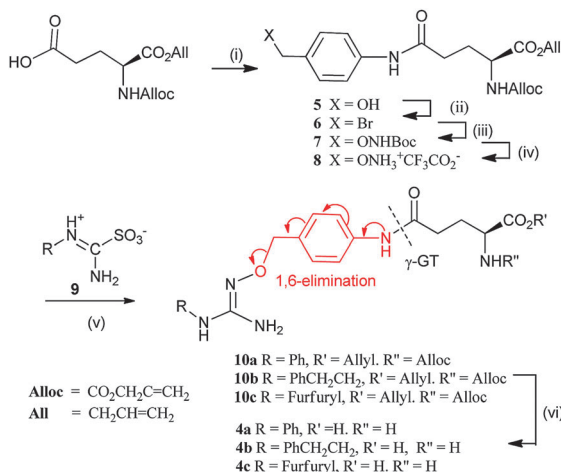


Scheme 2 Cyclization of direct coupling of NHGs with γ -glutamyl residue(s).



Scheme 3 Design of Glu/Gaba linked γ -glutamyl NO-donor pro-drugs of NHG and hydroxamic acid.

On the other hand, **2b** could be purified by preparative HPLC but was found to be resistant to γ -GT-mediated cleavage *in vitro* and was considered not to be a useful pro-drug. This prompted the preparation of **3** (Scheme 3), involving the conjugation of only one GABA-Glu dipeptide onto a hydroxamic acid, an alternative NO-donor.¹¹ Compound **3** too, unfortunately, was found to be resistant to γ -GT mediated deacylation, suggesting that the GABA-Glu peptide linker is not suitable for γ -GT cleavage in this setting.



Scheme 4 Design and synthesis of aminobenzyl linked γ -glutamyl NO-donor pro-drugs of NHG: (i) 4-aminobenzylalcohol, EEDQ, DCM, rt, 12 h, 85%; (ii) PBr₃, THF, 0 °C, 2 h, 87%; (iii) BocNHOH, NaH, THF, 0 °C, 4 h, 83%; (iv) CF₃CO₂H, DCM, 92%; (v) **9a** R = Ph or **9b** R = PhCH₂CH₂ or **9c** R = furfuryl, Et₃N, DMAP, DCM, 38–53%; (vi) [Pd(PPh₃)₄], PhSiH₃, DCM, 37–89%.

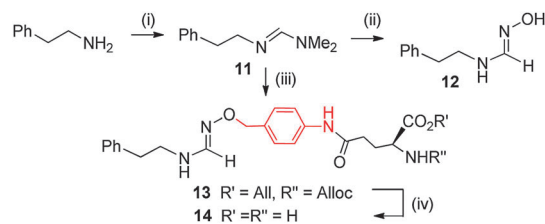
γ -Glutamyl anilines are known substrates for γ -GT²³ and presented an alternative linker option. The success of such an approach would involve a 1,6-elimination following the action of γ -GT on *N*- γ -glutamylaminobenzyl-oxo-guanidine **4a–c**, as illustrated in Scheme 4. Similar spacers have been employed previously in anticancer pro-drug design.²⁴

In the event, the synthesis of **4a–c** was successfully accomplished through a six-step reaction sequence (Scheme 4). Firstly, γ -glutamylation of 4-aminobenzylalcohol with Alloc- γ -glutamic acid 1-allyl ester (Alloc-Glu-OAll) (ESI†; Scheme S1) gave benzyl alcohol **5**. Conversion of the benzylalcohol moiety to the corresponding bromide **6** followed by nucleophilic displacement with BocNHOH generated aminooxide **7**, and then treatment with CF₃COOH–DCM, gave the key intermediate **8** which was coupled with the required amino(alkyl/aryl)iminio-methanesulfonate **9a–c** to generate **10a–c**. Finally the All/Alloc groups were removed under neutral conditions with ([Pd(PPh₃)₄]/PhSiH₃) to give **4a–c**.

The same aminobenzyl linker was also used for the γ -glutamylation of *N*-hydroxyformamides (NHF) (Scheme 5). *N*-Hydroxy-*N*-(4-butyl-2-methylphenyl)formamide²⁵ and *N*-hydroxy-*N*-(3-chloro-4-morpholin-4-ylphenyl)formamide²⁶ have been documented as 20-hydroxyeicosatetraenoic acid (20-HETE) inhibitors. 20-HETE is a major metabolite of arachidonic acid and is a potent vasoconstrictor; localisation of an NHF would counter the effect of 20-HETE and induce a synergic vasodilation effect mediated by NO. Thus *N*'-hydroxyphenylethylformamide **12** was prepared in this study and converted to pro-drug **14**.

Pro-drugs **4a–c** and **14** were rapidly cleaved by γ -GT and they were completely deacylated after 1 h, as judged by LC-MS. Fig. 1(a) and (b) illustrates the LCMS trace of **4b** and the conversion of **4b** to deacylated intermediate **15** [M-Glu]⁺ by γ -GT. This was in clear contrast to the GABA-linked candidates **2b** and **3**, which proved to be resistant to the action of γ -GT. 1,6-Elimination and loss of the linker from **15** to generate the parent NHG **1b** is significantly slower (trace amount of parent **1b** was detected by selective ion monitoring at *m/z* 180) than the cleavage of the γ -glutamyl moiety. In preliminary experiments with animal tissue, LC-MS analysis revealed ~90% conversion of **4b** (100 μ M) to **1b** in a rat renal homogenate (37 °C; 45 min). In addition, **4b** was found to induce substantial vasodilation in rat isolated perfused kidney preparations (50% of maximum vasodilation induced by ~40 μ M **4b**). Details of the bioactivity of these pro-drugs will be reported elsewhere.

In summary, several candidate NO-donor pro-drugs have been prepared, designed for activation by γ -GT. The pro-drugs



Scheme 5 Synthesis of *N*-hydroxyformamide and its glutamyl pro-drug: (i) Me₂NCH(OMe)₂, reflux, 2 h, quantitative; (ii) NH₂OH·HCl, MeOH, 63%; (iii) **8**, THF, reflux, 29%; (iv) [Pd(PPh₃)₄], PhSiH₃, DCM, rt, 6 h, 53%.

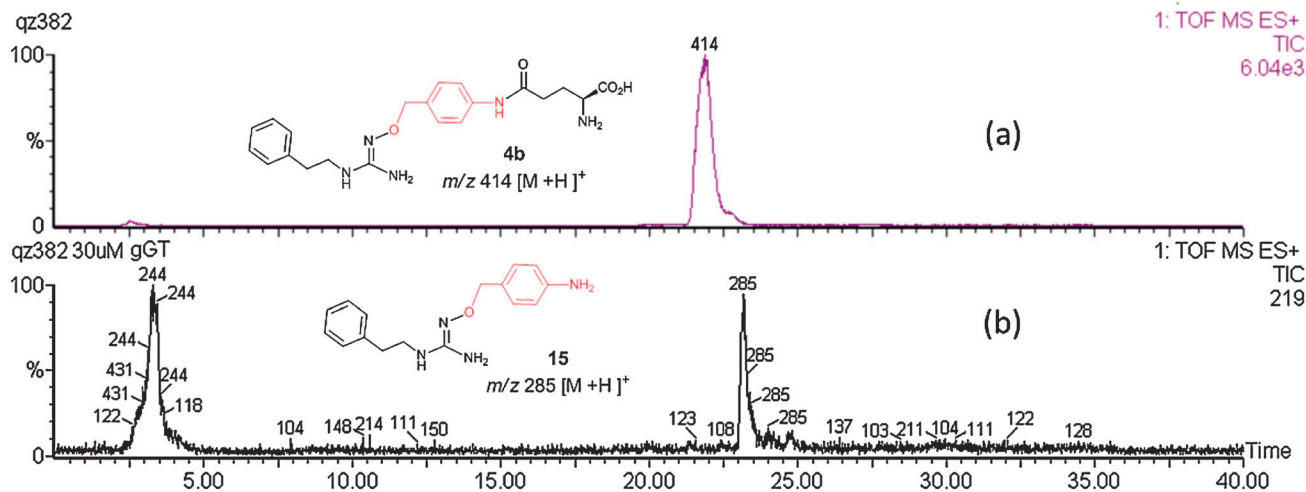


Fig. 1 LCMS trace of **4b** incubated in Krebs buffer at 37 °C for 1 h (a) without γ -GT and glutamyl acceptor Gly-gly, **4b** is intact; (b) with γ -GT (100 mU mL⁻¹) and glutamyl acceptor Gly-gly (5 mM), **4b** is deglutamylated to give the species **15**.

comprise the parent NO-donor, a linker and a γ -glutamyl moiety. GABA-linked pro-drugs are not suitable substrates for γ -GT, but those linked by the aminobenzyl moiety proved to be good substrates for the enzyme. The γ -glutamyl group is cleaved rapidly, with a slower decomposition of the aminobenzyl linker. Improved design is now focussed on tuning the spacer to encourage a more rapid release of the parent NHG drug.

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