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Intramolecular epoxide ring opening cyclisation reactions involving guanidines

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Abstract
The cyclisation of N-allyl- and N-homoallylguanidines using DMDO leading to the formation of novel 5- and 6-membered guanidine heterocycles is reported. Several of the products formed displayed weak inhibition of glycosidase enzymes.

Keywords: guanidines, epoxides, iodocyclisations, galactosidase inhibition, DMDO, epoxidation

Introduction
As part of a project directed towards the synthesis of marine natural products, we have previously reported the intramolecular cyclisation of guanidine epoxides and the cyclisation of allyl and homoallyl substituted guanidines using DMDO, I2/K2CO3 and under palladium catalysed conditions. We take this opportunity to report our findings on the oxidative cyclisation reactions in full.

Epoxide ring opening using guanidines
Very few examples of epoxide ring opening processes utilising guanidines have been reported and our preliminary investigations focused on the addition of guanidine to the simple epoxide 1. We treated 1 with guanidine in t-BuOH at room temperature for 24 h to effect N-alkylation of guanidine, which we presumed to be faster than the epoxide ring opening process. At this point, potassium t-butoxide was added to regenerate the free guanidine from its salt, following which the reaction was heated at 60°C for a further 48 h to affect cyclisation to give the 5-membered guanidine 2 (Scheme 1). In our previous work, we had reported efforts to purify 2 by column chromatography and had succeeded in obtaining product of relatively high purity (> 95 %) though it was apparent that it was contaminated with what appeared to be polymeric material. We also tried to purify 2 by derivatisation as its t-butyldimethylsilyl ether 3. However this proved difficult as the compound was prone to hydrolysis on chromatography which was thought to be promoted by the anchimeric assistance or the guanidinium group. We were however able to purify 2 by HPLC and on examination of higher field NMR data, it was apparent that significant quantities of a contaminant were present. Indeed re-examination of the crude reaction product indicated a ca 9:1 ratio of 2 and what was though to be the isomeric 4. Compound 4 gave signals at δ 3.33 (2H, dd, J 3.1, 12.3, 2 x CH), 3.45, (2H, dd, J 2.7, 12.3 Hz, 2 x CH) and 4.38 (1H, tt, J 2.7, 3.1 Hz, CH) ppm and this 6-endo-tet isomer 4 could possibly be formed by the attack of the guanidine on the CH2 of the epoxide after alkylation or
more likely by initial epoxide opening by guanidine followed by the 6-exo-tet displacement of bromine.

\[
\text{BrO} \xrightarrow{(a)} \text{NH} \xrightarrow{(b)} \text{TBSO}
\]

**Scheme 1**: (a) (i) Guanidine hydrochloride, tBuOK, tBuOH, then epoxide 1 16 h, rt. (ii) tBuOK, 60°C, 24 h. (iii) CF₃CO₂H, MeOH. (c) (i) 3 equiv. TBSCl, Imid., DMF, 16-24 h. (ii) NaBF₄ (sat., aq.).

We wished to prepare 4 independently and thus reacted nitroguanidine 5 with 1,3-diaminopropan-2-ol 6 at 70°C in water to give 5-hydroxy-2-nitrimino-1,3-diazacyclohexane 7 in 27% yield, which on hydrogenation in aqueous acetic acid gave 4 as its acetate salt in 75% yield (Scheme 2). Spectroscopic data for the synthetic sample of 4 corresponded exactly to the impurity found in the previous reactions.

\[
\text{H₂N} \xrightarrow{(a)} \text{H₂N} \xrightarrow{(b)} \text{H₂N}
\]

**Scheme 2**: (a) Water, 70 °C, 2 h (b) (a) H₂, 5 % Pd/C, 15% aqueous acetic acid 72 h.

Because of the problems with this impurity and problems associated with purification of the guanidine salts in these reaction we turned our attention to the reaction of the protected guanidines 8a and 8b and their reaction with the epoxidising agent DMDO. We had previously shown that the N-allyl-bis-Boc-guanidine 8a reacts with DMDO in acetone at -20 °C to give an intermediate epoxide 9a as evidenced by signals at δH 2.62 (1H, dd, J 2.4, 4.2 Hz, CH), 2.80 (1H, dd, J 4.4, 4.5 Hz, CH) and 3.14-3.22 (1H, m, CH) ppm. On continued stirring this intermediate was consumed to give, on careful work up and chromatography, a 62% yield of the cyclic product 10a the structure of which was confirmed by X-ray analysis. On attempted repeat of this reaction it was observed that a second isomeric product was always formed in the reaction and, on isolation of this, X-ray crystallography confirmed the structure of the product as the rearranged product 11a isolated in 63% yield. A similar migration of a Boc-group was reported in an N-Boc-protected 5-membered amide so this result is not surprising. More conveniently, a complete conversion of 10a into 11a could be effected if a solution of the crude reaction mixture in dichloromethane was stirred with silica gel overnight or by stirring in methanol containing a small amount (ca. 5%) of water. A similar result was observed with the Z-protected guanidine 8b which was again treated with an excess of DMDO in acetone at -20 °C and the reaction monitored by proton NMR. Epoxidation was found to occur rapidly as evidenced by signals at δH 2.61 (1H, dd, J 2.8, 4.5 Hz, CH), 2.80 (1H, dd, J 4.4, 4.5 Hz, CH) and 3.16-3.22 (1H, m, CH) ppm for epoxide 9b, but on continued stirring signals at δH 3.45 (1H, t, J 5.8 Hz, CH), 3.51 (1H,
dd, J 5.1, 5.7 Hz, CH), 3.87 (1H, dd, J 3.0, 5.5 Hz, CH), 3.92 (1H, dd, J 2.8, 5.8 Hz, CH), and 4.03-4.11 (1H, m, CH) ppm appeared which are evident of the structure 10b. However, after purification on silica gel, a new product was formed in 64% yield, which had a considerably simpler spectrum with signals at $\delta_H$ 3.20 (1H, dd, J 10.2, 4.0 Hz, CH), 3.45-3.51 (1H, m, CH) and 3.87-3.95 (3H, m, CH, CH$_2$) ppm and the two guanidine protons at $\delta_H$ (7.50-9.60 (2H, br s, 2 x NH) which assigned the structure as 11b. Again it was possible to effect this rearrangement by stirring the crude reaction product with silica gel in dichloromethane or by stirring in methanol containing a small amount (ca. 5 %) of water. Finally, deprotection of 1a was accomplished by treatment with excess trifluoroacetic acid in dichloromethane for 4 h to give guanidine 2 in 98 % yield (Scheme 3).

![Scheme 3](image)

**Scheme 3:** (a) DMDO, acetone, -20 °C-rt, 3 days. (b) Silica gel, CH$_2$Cl$_2$ or MeOH/H$_2$O (95:5), 16-24 h. (c) CF$_3$CO$_2$H, CH$_2$Cl$_2$, 0 °C-rt, 4 h.

We were interested in the mechanism of the Boc- and Cbz-group migration and in order to investigate this a 1:1 mixture of 8a and 8b was treated with DMDO at -20 °C and stirred at rt for 5 days at which point the formation of a mixture of 10a and 10b was formed as indicated by $^1$H NMR. This mixture was then dissolved in a mixture of methanol and water and stirred overnight at room temperature. Analysis of the product from this reaction by mass spectrometry confirmed the presence of three different ions with m/z peaks at 316.1867 and 350.1710 Daltons corresponding to the [M+H]$^+$ ions for 11a and 11b as well as a mass at 384.1552 which correspond closely to the [M+H]$^+$ ion for 11c/11d. This observation suggest that the migration of the protecting groups is not exclusively intramolecular and some evidence of intermolecular rearrangement is apparent. However, this may be happening in the initial DMDO stage of the process (Scheme 4).

![Scheme 4](image)
Following this work, we investigated the epoxidation of the dimethylallyl guanidine \(8c^3\) and found that on treatment with DMDO an epoxide \(12a\) was formed after 16 hours which gave distinctive signals at \(\delta H 2.95 (1H, dd, J 4.2, 7.4 Hz, CH), 3.24 (1H, ddd, J 4.4, 7.4, 14.3 Hz, CH), 3.98 (1H, ddd, J 4.2, 6.6, 14.3 Hz CH) ppm\) for the three methine protons. This epoxide slowly underwent ring opening to give some evidence for the formation of the 5-membered guanidine \(13a\) but this was transient and the rearranged \(14a\) was formed after stirring for 7 days. Attempted purification of this material was difficult as the product obtained was a gum which could not be recrystallised and was also prone to decomposition on silica gel. A similar reaction of bis-Z protected \(8d^3\) gave as a stable product the epoxide \(12b\) (\(\delta H 2.87 (1H, dd, J 4.1, 7.4 Hz, CH), 3.13 (1H, ddd, J 4.7, 7.4, 14.3 Hz, CH) and 3.88 (1H, ddd, J 6.5, 14.3 Hz, CH) ppm\) which on attempted recrystallisation from dichloromethane/petrol deposited a precipitate of the cyclised and rearranged 5-membered guanidine \(14b\). Distinctive signals were observed at \(\delta H 3.30 (1H, dd, J 10.3, 6.4 Hz, CH), 3.51 (1H, app t, J 10.3 Hz, CH) and 4.12 (1H, dd, J 10.3, 6.4 Hz, CH) ppm\) for the three methyne protons with 2 guanidine NH signals at \(\delta H 8.19 (1H, br s, NH) and 8.93 (1H, br s, NH) ppm\). Conclusive proof of the 5-membered system was given in the carbon spectrum with the CH-N signal at \(\delta C 61.3 ppm\), whilst the quaternary C-O appeared at \(\delta C 84.3 ppm\). The slow rearrangement could be accelerated if a solution of the crude reaction mixture in dichloromethane was stirred with silica gel overnight, to give an 87 % yield of \(14b\). Hydrogenation of \(14b\) over Pd/C gave \(15\) in 42 % yield after purification (Scheme 5).

Following this the DMDO cyclisation of the homoallyl guanidine \(8e^3\) was investigated and again this underwent epoxidation and cyclisation to give the 6-membered guanidine \(16\) which on treatment with silica gel gave \(17\) in 82% yield, the structure being determined by X-ray crystallography. Deprotection of this compound with excess trifluoroacetic acid in chloroform for 24 h gave \(18\) in 66 % yield. The epoxidation reaction of the Boc-protected guanidine \(8f^3\) using DMDO under identical conditions was also performed, and on completion, the crude
product 16 was dissolved in methanol/water. After stirring at rt for 4 days, purification by column chromatography gave 19a in 72% yield. The structure of 19a was confirmed by X-ray crystallographic analysis (Figure 1). Finally, epoxidation of the Cbz-protected guanidine 8g under identical conditions, followed by rearrangement in methanol/water gave 19b in 79%. This could be improved to give a 95% yield by treatment of the crude reaction mixture from the epoxidation step with TFA in MeOH for 24 h at rt (Scheme 6).

We next investigated the epoxidation of the hydroxy-substituted allyl guanidines 20 and homoallyl guanidine 24. Thus 20 was treated with an excess of DMDO at -20 °C in acetone and the mixture stirred to rt for 48
h following which the reaction mixture was evaporated and the crude product dissolved in a methanol/water mixture and the mixture stirred for 24 h. Analysis of the product 21 indicated a mixture of several isomeric compounds relating to the migration of the Boc-protecting groups and this mixture was deprotected by treatment with trifluoroacetic acid in dichloromethane for 24 h. On evaporation, the cyclised product 22 was obtained in 19% overall yield for three steps after purification by HPLC. In a similar fashion homoallyl guanidine 24 (prepared by hydrolysis of the acetate 23) was treated with DMDO to give cyclised guanidines 25, which in turn was deprotected with trifluoroacetic acid in dichloromethane to give the guanidine 26 in 15% overall yield for three steps after purification by HPLC (Scheme 7).

![Chemical diagram]

**Scheme 7**: (a) DMDO, acetone, -20 °C-rt, 24 h. (b) MeOH/H2O (95:5). (c) CF3CO2H, CH2Cl2, rt, 24 h. (d) K2CO3, MeOH, 4 h.

**Biological activity**

We have reported previously that cyclic hydroxylated guanidines gave selective inhibition of β-galactosidase and glycosidases are involved in many disease states and there are many opportunities for therapeutic intervention both by inhibition and promotion of glycosidases. In addition, selectivity can be more important for drug development that potency and so we here report the comparative activity of the synthesised compounds on a range of glycosidases. The guanidines 3, 7, 15, 18, 22 and 26 were investigated for activity on a panel of commercially available glycosidases from Sigma (α-glucosidases [yeast and Bacillus], β-glucosidase [almond], α-galactosidase [Green coffee bean], β-galactosidase [bovine], α-mannosidase [Jack bean], hexosaminidases [bovine kidney, Jack bean] and β-glucuronidase [bovine liver] at a top concentration of 0.14 mg/ml. 5 mM p-nitrophenyl-substrates were used and the pH optima for the enzymes. Compound 3 showed no significant inhibition of any of the glycosidases. Compounds 7, 15 and 18 showed some weak inhibition of the Bacillus α-glucosidase but with less than 15% inhibition at the top concentration used (0.14 mg/mL in assay) with 18 also showing weak inhibition (12%) of the β-glucosidase but more marked inhibition of the β-galactosidase (47%). Whilst 22 showed no inhibition of most enzymes tested it showed a promotion of the bovine β-N-acetylglucosaminidase activity (18%) which was also shown by 26 (22%) Both compounds also weakly promoted the Jack bean hexosaminidase (8.6 and
17% respectively). Compound 26 also showed weak but unusual promotion of the α-mannosidase (23%) but had some inhibition of the β-galactosidase (30%). Whilst this inhibition and promotion displayed by these compounds is not strong, the selectivity is of interest, e.g. 7 and 15 mainly inhibiting the bacillus α-glucosidase. The promotion of glycosidase activity, by 22 and 26 for example, of the bovine hexosaminidase, suggests improved folding or stabilization of the glycosidase due to the molecule binding to it; improved glycosidase activity is of interest to treat enzyme deficiencies (e.g. Tay Sachs disease) and improved folding and function may prevent deposition of enzymes including hexosaminidase in neurodegenerative diseases.

Conclusions

The DMDO mediated cyclisation of allyl- and homo-allyl substituted guanidines is a useful and predictable method for the synthesis of 5- and 6-membered guanidine heterocycles. We have prepared a range of these heterocycles which displayed weak inhibition of glycosidase enzymes, however two compounds showed an interesting promotion of glycosidase activity which might be of interest. We are continuing our synthetic work in this area.

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Experimental

All glassware used was washed with acetone and dried with N₂ or in a vacuum oven. Reagents and starting materials were purchased from commercial suppliers and used as supplied. Diethyl ether and tetrahydrofuran were distilled from benzophenone and sodium wire, whilst dichloromethane was dried over CaH₂ and freshly distilled. DMF, chloroform and methanol were purchased as dry from Aldrich. Petrol refers to the fraction distilled between boiling range of 40-60 °C. Column chromatography and TLC chromatography was carried out using silica and silica plates purchased from Fluorochem Ltd (particle size 35-70 µ) using HPLC grade acetic acid (AA) chloroform (CFM), dichloromethane (DCM), diethyl ether (DE), ethyl acetate (EA), hexane (HX) and methanol (ME). Compounds were visualised using UV, iodine or stained using polyphosphomolybdic acid (PMA) in EtOH or vanillin in EtOH/H₂SO₄, with heating. IR spectra were recorded on a Perkin-Elmer 1600 series FTIR instrument as thin films, Nujol mulls, or chloroform solution on NaCl plates with absorption frequencies reported in wavenumbers (cm⁻¹). Routine NMR samples were performed on a Bruker AC250, AC400 or on a Bruker Avance-500 spectrometer. Chemical shifts for spectra are all reported in δ values (ppm) relative to the residual solvent peak in each case. Electron Ionisation (EI) and Chemical Ionisation (CI) mass spectra were recorded on an Agilent Tech. 6890N spectrometer or an XCalibur MAT900 XLT spectrometer at the EPSRC Mass Spectrometry Service (Swansea).

General conditions for epoxidation with DMDO⁸
A finely divided sample of the guanidine in a 250 mL RBF was cooled (-20 °C), whereupon a freshly prepared solution of DMDO\textsuperscript{8} (see SI) in acetone (100-150 mL) was added. The mixture was then stirred whilst slowly warming to rt overnight and further stirred for the required time.

**General condition for trifluoroacetic acid mediated Boc-deprotection.**
The Boc-protected guanidine is dissolved in dichloromethane (5 mL) and cooled (0 °C) whereupon trifluoroacetic acid (5 mL) was added slowly over 5 mins and the mixture stirred to rt for the indicated time. The reaction was then evaporated and the residue repeatedly co-evaporated with chloroform to remove traces of trifluoroacetic acid.

(2-amino-4,5-dihydro-1H-imidazol-4-yl)methanol 2,2,2-trifluoroacetate 2 and 2-amino-1,4,5,6-tetrahydropyrimidin-5-ol 2,2,2-trifluoroacetate 4

Potassium tert-butoxide (1.80 g, 16.1 mmol, 1.1 eqv.) was added to a cooled (5 °C) solution of guanidine hydrochloride (1.68 g, 17.5 mmol, 1.2 eq) in tert-butanol (30 mL) and the mixture was stirred to rt over 1 h. 60 minutes. Epibromohydrin (1.26 ml, 14.6 mmol) was then added over 5 mins and the mixture was stirred at rt for 62 h. Further potassium tert-butoxide (1.80 g, 16.1 mmol, 1.1 eqv.) was then added and the mixture heated (60 °C) for 24 h. The resultant white slurry was then cooled (0 °C) and TFA (5 mL) in methanol (15 mL) was added slowly over 10 mins and then mixture stirred to rt over 1 h. The reaction was evaporated onto silica gel (10 g) and purified by chromatography (gradient elution, 0-100 % ME in CFM) to give a ca. 9:1 mixture (NMR) of 2 and 4 (1.87 g) as their trifluoroacetate salts in 50% yield.

5-hydroxy-2-nitrnimino-1, 3-diazacyclohexane\textsuperscript{7}

A solution of nitroguanidine 5 (1.50 g, 16.6 mmol) and 1,3-diaminopropan-2-ol 6 (2.30 g, 16.6 mmol) were dissolved in water (60 mL) and the mixture heated at 70 °C for 2 h. The reaction mixture was cooled to rt and stirred for 12 h, then cooled (0 °C) and the precipitate formed collected by filtration and washed with chilled water (15 mL). The solid obtained was firstly air-dried then dried under vacuum (P\textsubscript{2}O\textsubscript{5}) to constant weight to give 7 (0.52 g, 27 % yield) as a white solid. Mp 230-233 °C (Lit\textsuperscript{7} 233-233.5 °C); δ\textsubscript{H} (500 MHz, D\textsubscript{2}O) 3.45 (2H, dd, J 3.1, 13.0, 2 x CH), 3.57, (2H, dd, J 2.6, 13.0 Hz, 2 x CH), 4.38 (1H, tt, J 2.6, 3.1 Hz, CH); δ\textsubscript{C} (125 MHz, D\textsubscript{2}O) 44.3, 58.1, 153.6; MS(CI) 114.0 (100 %, [M+H -NO\textsubscript{2}]\textsuperscript{+}) 160.0 (100%, [M+H\textsuperscript{+}]); HRMS (EI) C\textsubscript{4}H\textsubscript{8}N\textsubscript{4}O\textsubscript{3} [M+H\textsuperscript{+}], found 160.0589, requires 160.0591.

2-amino-1,4,5,6-tetrahydropyrimidin-5-ol acetate 4

Palladium on charcoal (5 %, 0.6 g) was added to a solution of guanidine 7 (0.473 g, 2.97 mmol) in aqueous acetic acid (15 % v/v, 50 mL) and the mixture stirred under H\textsubscript{2} (balloon) for 72 h. The reaction was filtered through a Celite\textsuperscript{®} pad and then evaporated and the crude product purified by chromatography (5-15 % ME in CFM, then 15% - 20% ME in CFM with 0.1 % acetic acid) to give 4 as a white solid (0.388 g, 75% yield). Rf 0.20 (15% ME in CFM with 0.1 % acetic acid); Mp 61-62 °C; δ\textsubscript{H} (500 MHz, D\textsubscript{2}O) 1.92 (3H, s, Me), 3.33 (2H, dd, J 3.1, 12.3, 2 x CH), 3.45, (2H, dd, J 2.7, 12.3 Hz, 2 x CH), 4.38 (1H, tt, J 2.7, 3.1 Hz, CH); \text{v}\textsubscript{max} 3340, 2981, 2865, 1579; δ\textsubscript{C} (125 MHz, D\textsubscript{2}O) 23.3, 43.9, 58.7, 153.6, 181.5; MS(CI) 116.1 (100 %, [M+H\textsuperscript{+}]); HRMS(CI) C\textsubscript{4}H\textsubscript{10}N\textsubscript{3}O [M+H\textsuperscript{+}], found 116.0817, requires 116.0818.

**tert-butyl 2-((tert-butoxycarbonyl)imino)-5-(hydroxymethyl)imidazolidine-1-carboxylate 10a**
Guanidine \(8a\) \((0.30 \text{ g}, 1.00 \text{ mmol})\) was epoxidised using the standard conditions to give a crude product \((0.33 \text{ g})\) which was purification using rapid chromatography (gradient elution: 10-100 \% EA in PE, then 10 \% ME in EA) to give \(10a\) \((196.0 \text{ mg}, 62 \% \text{ based on recovered } 8a\), \(11a\) \((40.0 \text{ mg}, 13\%, 14\% \text{ based on recovered } 8a\) and recovered \(8a\) \((40.0 \text{ mg}).\) Recrystallisation (EA/PE or DCM/DE) gave crystals suitable for X-ray analysis\(^1\);

\[\text{MP. } 130^\circ \text{C; }{\delta}_H(500 \text{ MHz, CDCl}_3) 1.42 \text{ (9H, s, } t{-}\text{Bu}), 1.46 \text{ (9H, s, } t{-}\text{Bu}), 3.63 \text{ (1H, br d, } J 11.3 \text{ Hz, CH}), 3.69-3.78 \text{ (3H, m, 3 x CH), 4.11-4.20 (1H, m, CH), 5.87 (2H, br s, NH, OH); }{\delta}_C(62.5 \text{ MHz, CDCl}_3) 28.1, 28.1, 48.8, 57.6, 62.3, 80.9, 83.6, 150.9, 152.9, 155.7; {\nu}_{\text{max}} 3346, 2983, 2975, 1753, 1743, 1600, 1141; \text{MS(CI)} 316.1 (100\%, [M+H+]); \text{HRMS(CI)} C_{14}H_{26}N_3O_5 \text{ [M+H+]}, \text{found 316.1868, requires 316.1867.}\]

**tert-butyl-(4-(((tert-butoxycarbonyl)oxy)methyl)imidazolidin-2-ylidene)carbamate 11a.**

Guanidine \(10a\) and silica gel (ca. 1 g) in chloroform (20 mL) were stirred at rt for 72 h then filtered through a Celite\(^\circ\) pad which was washed with chloroform and ethyl acetate. Evaporation of the solvent gave a crude compound which was recrystallised from chloroform by slow evaporation to give crystals of \(11a\) \((70.3 \text{ mg}, 64\% \text{ yield})\) suitable for X-ray analysis.\(^2\)

\[\text{MP. } 92-94 ^\circ \text{C; }{\delta}_H(500 \text{ MHz, CDCl}_3), 3.40 \text{ (1H, dd, } J 6.0, 9.7 \text{ Hz, CH}), 3.73 \text{ (1H, dd, } J 9.6, 9.7 \text{ Hz, CH}), 4.07 \text{ (1H, dd, } J 6.6, 10.9 \text{ Hz, CH}), 4.10 \text{ (1H, dd, } J 5.5, 10.9 \text{ Hz, CH}), 4.16 \text{ (1H, dddd, } J 5.5, 6.0, 6.6, 9.67 \text{ Hz, CH}), 6.67-8.86 \text{ (2H, br s, 2 x NH); }{\delta}_C(125 \text{ MHz, CDCl}_3) 44.7, 52.5, 66.6, 68.3, 70.0, 127.9, 128.0, 128.5, 128.7, 135.1, 137.3, 154.8, 162.3, 164.3; {\nu}_{\text{max}} 3377, 2961, 1753, 1659, 1617, 1255; \text{MS(CI)} 316.2 (100\%, [M+H+]); \text{HRMS(ES)} C_{14}H_{26}N_3O_5 \text{ [M+H+], found 316.1558, requires 316.1554.}\]

**Benzyl (4-((((benzyloxy)carbonyl)oxy)methyl)imidazolidin-2-ylidene)carbamate 11b**

Compound \(8b\) \((0.309 \text{ g, 0.84 mmol})\) was epoxidised under the general conditions for 5 days to give a crude cyclised product \((0.35 \text{ g})\) which was dissolved in dichloromethane (5 ml) and silica gel (1 g) was added and the slurry stirred overnight. Evaporation of the dichloromethane and column chromatography of the residue (0-100 \% EA in PE) gave \(11b\) \((0.208 \text{ g, 0.54 mmol, 64\%})\) as a white solid.

\[\text{MP 155-157 ^\circ \text{C; } Rf 0.46 (EtOAc); }{\delta}_H(500 \text{ MHz, CDCl}_3), 3.20 \text{ (1H, dd, } J 4.0, 10.2 \text{ Hz, CH}), 3.45-3.51 (1H, m, CH), 3.87-3.95 (3H, m, CH, CH2), 4.94 (2H, s, CH2), 5.03 (2H, s, CH2), 7.10-7.30 (10H, m, 2 x Ph), 7.50-9.60 (2H, br s, 2 x NH); {\delta}_C(125 \text{ MHz, CDCl}_3) 44.7, 52.5, 66.6, 68.3, 70.0, 127.9, 128.0, 128.5, 128.7, 135.1, 137.3, 154.8, 162.3, 165.3; {\nu}_{\text{max}} 3398, 3150, 3065, 3035, 2956, 1748, 1654, 1654, 1263, 1264; \text{MS(CI)} 384.2 (33 \% , [M+H+]); \text{HRMS(ES)} C_{20}H_{22}N_3O_5 \text{ [M+H+], found 384.1558, requires 384.1554.}\]

**(2-iminoimidazolidin-4-yl)methanol 2,2,2-trifluoroacetate 2**

Guanidine \(11a\) \((134 \text{ mg}, 0.425 \text{ mmol})\) was deprotected under the standard conditions to give \(2\) \((96.0 \text{ mg})\) as a gum in 98 \% yield.

\[\text{\delta}_H(250 \text{ MHz, CD}_3OD) 3.50 \text{ (1H, dd, } J 6.1, 9.8 \text{ Hz, CH}), 3.54 \text{ (1H, dd, } J 5.2, 11.4 \text{ Hz, CH}), 3.62 \text{ (1H, dd, } J 4.5, 11.4 \text{ Hz, CH}), 3.75 \text{ (1H, dd, } J 9.8, 9.8 \text{ Hz CH}), 4.07 \text{ (1H, dddd, } J 4.5, 5.2, 6.1, 9.8 \text{ Hz, CH}); {\delta}_C(125 \text{ MHz, CD}_3OD) 46.1, 58.1, 63.9, 161.4; {\nu}_{\text{max}} 3352, 2943, 1552; \text{MS(CI)} 116 (40 \% [M+H+]); \text{HRMS(CI)} C_4H_10N_3O \text{ [M+H+], found 116.0825, requires 116.0818.}\]

**tert-Butyl (Z)-(5-(((tert-butoxycarbonyl)oxy)-4,4-dimethyltetrahydropyrimidin-2(1H)-ylidene)carbamate 14a**

Compound \(8c\) \((0.399 \text{ g, 1.22 mmol})\) was epoxidised under the general conditions and after 16 hours the epoxide \(12a\) was formed as evidenced by proton NMR (\(\text{\delta}_H\) (500 MHz, CDCl\(_3\)), 1.32 (3H, CH\(_3\)), 1.33 (3H, CH\(_3\)), 1.35 (3H, CH\(_3\)), 3.66 (1H, dd, J 6.1, 9.8 Hz, CH), 3.70 (1H, dd, J 5.2, 11.4 Hz, CH), 3.78 (1H, dd, J 4.5, 11.4 Hz, CH), 3.87 (1H, dd, J 9.8, 9.8 Hz CH), 4.03 (1H, dddd, J 4.5, 5.2, 6.1, 9.8 Hz, CH); \(\text{\delta}_C(125 \text{ MHz, CD}_3OD) 46.1, 58.1, 63.9, 161.4; {\nu}_{\text{max}} 3352, 2943, 1552; \text{MS(CI)} 116 (40 \% [M+H+]); \text{HRMS(CI)} C_4H_10N_3O \text{ [M+H+], found 116.0825, requires 116.0818.}\]
1.49 (9H, s, tBu), 1.50 (9H, s, tBu), 2.95 (1H, dd, J 4.2, 7.4 Hz, CH), 3.24 (1H, ddd, J 4.4, 7.4, 14.3 Hz, CH), 3.98 (1H, ddd, J 4.2, 6.6, 14.3 Hz CH), 8.57 (1H, broad s, NH), 11.47 (1H, broad s, NH) ppm), which cyclised slowly to give 14a as a oil in quantitative yield. After work up, attempted purification by column chromatography or recrystallization led to considerable decomposition. δH (250 MHz, CDCl3) 1.21 (3H, CH3), 1.22 (3H, CH3), 1.49 (9H, s, tBu), 1.55 (9H, s, tBu), 3.83 (1H, dd, J 2.5, 12.8 Hz, CH), 3.86 (1H, dd, J 8.9, 12.8 Hz, CH), 4.22 (1H, dd, J 2.7, 8.5 Hz CH), 2 x NH not observed. δC (62.5 MHz, CDCl3) 20.9, 21.0, 27.8, 28.2, 43.3, 61.2, 79.9, 82.1, 82.8, 151.7, 160.2, 163.0; νmax 3346, 1748, 1656, 1611, 1368, 1315, 1251, 1143, 998; MS (CI) 188.1 (100 %), 232.1 (75 %), 288.2 (25 %), 244.2 (100 %, [M+H+]; HRMS (CI) C16H30N3O5 [M+H+], found 344.2178, requires 344.2180.

Benzyl (Z)-(5-(((benzyloxy)carbonyl)oxy)-4,4-dimethyltetrahydropyrimidin-2(1H)-ylidene)carbamate 14b

Compound 8d3 (0.42 g, 1.13 mmol) was epoxidised under the general conditions for 5 days to give the crude epoxide 12b (0.46 g) as a white solid. δH (500 MHz, CDCl3) 1.21 (3H, CH3), 1.22 (3H, CH3), 2.87 (1H, dd, J 4.1, 7.4 Hz, CH), 3.13 (1H, ddd, J 4.7, 7.4, 14.3 Hz, CH) 3.88 (1H, ddd, J 4.1, 6.5, 14.3 Hz, CH), 5.04 (2H, s, CH2), 5.07 (2H, s, CH2), 7.16-7.31 (10H, m, 2 x Ph), 8.46 (1H, broad dd, J 4.7, 6.5 Hz, NH), 11.66 (1H, broad s, NH). The epoxide 12b (0.46 g) was dissolved in a minimum amount of dichloromethane (2-3 ml) and diluted with PE (10-15 ml) and placed in a freezer. After 3 days a white amorphous precipitate was obtained. Removal of the supernatant liquid and drying of the solid gave 14b (100.0 mg, 23%) as a solid. The supernatant liquid was evaporated and re-dissolved in dichloromethane (10 mL), whereupon silica gel (ca. 0.3 g) was added and the mixture stirred for 48 h. After filtration and evaporation the crude product (0.36 g) was dissolved in dichloromethane (3-4 mL) and diluted with petrol (20-25 mL) and on cooling for 2-3 days a further sample of 14b (277.0 mg, 64%) was formed giving an overall yield of 87%. δH (500 MHz, CDCl3) 1.42 (3H, s, CH3), 1.45 (3H, s, CH3), 3.30 (1H, dd, J 10.3, 6.4 Hz, CH), 3.51 (1H, t, J 10.3 Hz, CH) 4.12 (1H, dd, J 10.3, 6.4 Hz, CH) 5.07 (1H, d, J 12.3 Hz, CH), 5.09 (1H, d, J 12.3 Hz, CH), 5.13 (2H, s, CH2), 7.27-7.43 (10H, m, 2 x Ph), 8.19 (1H, br s, NH), 8.93 (1H, br s, NH); δC (125 MHz, CDCl3) 20.7, 20.7, 42.8, 61.3, 66.5, 69.3, 84.3, 127.9, 128.0, 128.4, 128.6, 128.7, 135.3, 137.3, 153.2, 163.4, 165.4; νmax 3383, 3074, 3037, 2985, 2928, 2857, 1741, 1654, 1624, 1270, 1253, 1107; MS (CI) 412 (100%, [M+H+]) HRMS (CI) C22H26N3O5 [M+H+], found 412.1869, requires 412.1867.

4-(2-hydroxypropan-2-yl)imidazolidin-2-iminium hydrogen carbonate 15

Guanidine 14b (52.6 mg, 0.128 mmol) was dissolved in methanol (3 mL), Pd/C (10 %, 120 mg) was added and the mixture stirred under hydrogen gas (balloon) for 2 h. After filtration HCl (1M ca 2-3 drops) was added and the mixture evaporated to give 15.HCl (17.2 mg, 0.096 mmol) as a gum in 75% yield. This was dissolved in a 1:1 mixture of EtOH/H2O (0.5 ml) and applied to a column of Amberlite CG400 (2 x 1 cm, OH- form, the resin having previously been washed to neutrality with water) on eluting with water, three fractions (2 mL, 2 mL and 5 mL) gave 15 (11.0 mg) in 42% yield as the hydrogen carbonate salt. δH (400 MHz, D2O) 1.16 (3H, s, CH3), 1.21 (3H, s, CH3), 3.58 (1H, dd, J 10.1, 6.6 Hz, CH), 3.75 (1H, dd, J 10.1, 10.2 Hz CH), 3.98 (1H, dd, J 10.2, 6.6 Hz, CH); δC (100 MHz, D2O) 23.3, 24.4, 43.9, 63.3, 71.4, 159.7, 165.1; νmax 3320, 3212, 2973, 2924, 2852, 1688, 1579, 1404, 1281, 1174, 1106, 1015, 950; MS (CI) 414.1 (100%, [M+H+]); HRMS (CI) C22H26N3O5 [M+H+], found 414.1127, requires 414.1131.

tert-butyl (Z)-(4-(((tert-butoxycarbonyloxy)methyl)tetrahydropyrimidin-2(1H)-ylidene)carbamate 17
Compound 8e<sup>3</sup> (0.51 g, 1.63 mmol) was epoxidised under the general conditions for 3 days to give a crude cyclised product (0.53 g) which was dissolved in dichloromethane (5 mL) and silica gel (2 g) added and the mixture stirred for 16 h. The suspension was evaporated and compound purified by chromatography (0-10% ME in EA) and the product obtained recrystallised (EA:PE 1:2) to give 17 (0.44 g, 1.33 mmol) in 82% yield as pale yellow diamond shaped crystals. R<sub>f</sub> 0.27 (10:90 ME:EA); δ<sub>HH</sub> (500 MHz, CDCl<sub>3</sub>) 1.45 (9H, s, tBu), 1.47 (9H, s, tBu), 1.79-1.85 (1H, m, CH), 1.97-2.01 (1H, m, CH), 3.37 (1H, ddd, J 4.5, 8.1, 13.1, CH), 3.42-3.46 (1H, m, CH), 3.74-3.79 (1H, m, CH), 4.06 (1H, dd, J 6.6, 11.1, CH), 4.13 (1H, dd, J 5.7, 11.1), 6.90-10.3 (2H, br s, 2 x NH); δ<sub>CC</sub> (125 MHz, CDCl<sub>3</sub>) 22.4, 27.8, 28.3, 36.8, 47.9, 67.7, 80.0, 83.1, 153.1, 155.9, 159.2; ν<sub>max</sub> (Nujol mull) 3152, 2724, 1747, 1632, 1594, 1454, 1376, 1156; MS(CI) <sup>m/z</sup> 330.3 (100 %, [M+H]<sup>+</sup>); HRMS(ES) C<sub>15</sub>H<sub>27</sub>N<sub>3</sub>O<sub>5</sub> [M+H<sup>+</sup>], found 330.2019, requires 330.2023.

(2-Iminohexahydropyrimidin-4-yl)methanol 2,2,2-trifluoroacetate 18

Compound 17 (38.2 mg was deprotected over 14 h using the standard method to give 18 (18.5 mg, 0.076 mmol in 66% yield as a glass after chromatography (0-10 % ME in DCM). R<sub>f</sub> 0.27 (20 % ME in DCM); δ<sub>HH</sub> (500 MHz, CD<sub>3</sub>OD) 1.70-1.78 (1H, m, CH), 1.96-2.02 (1H, m, CH), 3.31 (1H, ddd, J 4.3, 9.3, 12.6, CH), 3.40 (1H, dt, 12.6, 5.0 Hz), 3.48-3.54 (2H, m, 2 x CH), 3.64-3.69 (1H, m, CH); δ<sub>CC</sub> (125 MHz, CD<sub>3</sub>OD) 23.3, 38.0, 52.0, 116.1 (q, J<sub>CF</sub> 285 Hz), 155.9, 159.0 (q, J<sub>CF</sub> 41 Hz); ν<sub>max</sub> 3332, 3264, 3095, 2960, 2926, 2855, 1791, 1681, 1632, 1429, 1338, 1260, 1176, 1031, 835, 801, 712; MS(CI) 130.1 ([M+H +]); HRMS(ES) C<sub>5</sub>H<sub>12</sub>N<sub>3</sub>O [M+H<sup>+</sup>], found 130.0975, requires 130.0975.

tert-Butyl(4-(((tert-butoxycarbonyl)oxy)methyl)-4-methyltetrahydropyrimidin-2(1H)-ylidene)carbamate 19a

Compound 8f<sup>3</sup> (0.330 g, 1.01 mmol) was epoxidised under the general conditions for 16 hrs to give a crude cyclised product (0.35 g) on evaporation which was dissolved in dichloromethane, dried (MgSO<sub>4</sub>), filtered and evaporated in vacuo. The resulting product was dissolved in methanol (5 mL) and water (0.1 mL) and stirred for 4 days, evaporated and purified column chromatography (20-100% EA in PE) to give 19a (0.250 g, 0.73 mmol in 72% yield as a white solid. The solid was dissolved in dichloromethane and hexane was added to the cloud point whereupon cooling (-20 °C) gave crystals suitable for X-ray analysis (Figure 1). R<sub>f</sub> 0.03 (EA); Mp 143-145°C; ν<sub>max</sub> 3261, 2978, 2931, 1745, 1714, 1644; δ<sub>HH</sub> (500 MHz; CDCl<sub>3</sub>) 1.35 (3H, s CH<sub>3</sub>), 1.46 (9H, s, 3 x CH<sub>3</sub>), 1.47 (9H, s, 3 x CH<sub>3</sub>), 1.71 (1H, ddd, J 5.5, 7.6, 13.4, CH), 1.93-2.00 (1H, m, CH), 3.37-3.48 (2H, m, CH<sub>2</sub>), 3.96 (1H, d, J 11.1 Hz, CH), 4.08 (1H, d, J 11.1 Hz, CH), 5.17 (2H, s, CH<sub>2</sub>), 5.24 (2H, s, CH<sub>2</sub>), 7.32-7.42 (10H, m, 2 x Ph); δ<sub>CC</sub> (125 MHz; CDCl<sub>3</sub>) 24.6, 27.8, 28.0, 35.7, 52.4, 70.6, 83.6, 85.2, 153.1, 153.4; HRMS(ES) C<sub>16</sub>H<sub>30</sub>N<sub>3</sub>O<sub>5</sub> [M+H<sup>+</sup>], found 344.2184, requires 344.2180.

Benzyl (4-(((benzyloxy)carbonyl)oxy)methyl)-4-methyltetrahydropyrimidin-2(1H)-ylidene)carbamate 19b

Compound 8f<sup>3</sup> (0.50 g, 1.26 mmol) was epoxidised under the general conditions for 16 hrs to give a crude cyclised product (0.55 g) on evaporation which was dissolved in dichloromethane, dried (MgSO<sub>4</sub>), filtered and evaporated in vacuo. The resulting product was dissolved in methanol (5 mL) and water (0.1 mL) and stirred for 4 days, evaporated and purified column chromatography (20-100% EA in PE) to give 19b (0.49 g, 0.73 mmol in 72% yield as a white solid. The solid was dissolved in dichloromethane and hexane was added to the cloud point whereupon cooling (-20 °C) gave crystals suitable for X-ray analysis (Figure 1). R<sub>f</sub> 0.03 (EA); Mp 143-145°C; ν<sub>max</sub> 3261, 2978, 2931, 1745, 1714, 1644; δ<sub>HH</sub> (500 MHz; CDCl<sub>3</sub>) 1.35 (3H, s CH<sub>3</sub>), 1.46 (9H, s, 3 x CH<sub>3</sub>), 1.47 (9H, s, 3 x CH<sub>3</sub>), 1.71 (1H, ddd, J 5.5, 7.6, 13.4, CH), 1.93-2.00 (1H, m, CH), 3.37-3.48 (2H, m, CH<sub>2</sub>), 3.96 (1H, d, J 11.1 Hz, CH), 4.06 (1H, d, J 11.1 Hz, CH), 5.23 (2H, s, 2 x NH); δ<sub>CC</sub> (125 MHz; CDCl<sub>3</sub>) 24.6, 27.8, 28.0, 35.7, 52.4, 70.6, 83.6, 85.2, 153.2, 153.4; HRMS(ES) C<sub>16</sub>H<sub>30</sub>N<sub>3</sub>O<sub>5</sub> [M+H<sup>+</sup>], found 344.2184, requires 344.2180.
9.84 (2H, br s, NH); δc (125 MHz; CDCl3) 24.6, 27.9, 35.7, 52.2, 68.5, 70.5, 71.7, 128.3, 128.7, 128.8, 128.8, 129.0, 134.8, 135.0, 152.3, 154.7, 155.3; v_{max} 3243, 3154, 3064, 3032, 2955, 2928, 2896, 1748, 1644, 1634, 1562, 1554; HRMS(ES) C_{22}H_{26}N_{3}O_{5} ([M+H^+]\text{)}, found 412.1867, requires 412.1867.

+/- (R)-1-((S)-2-iminoimidazolidin-4-yl)ethane-1,2-diol 2,2,2-trifluoroacetate 22

Compound 20\textsuperscript{4} (0.431 g 1.308 mmol) was epoxidised under the general conditions for 48 hrs to give crude product (490 mg) which was dissolved in MeOH (5 mL) to which water (ca. 0.2 mL) was added and the mixture stirred. After 24 h the reaction was evaporated to give crude 21 (451 mg) which was used in the next step without further purification. Compound 21 (451 mg) was then deprotected using the standard method over 24 h. Evaporation gave a gum (394 mg) which was purified by preparative HPLC (ACE 10 C18 250 x 21.8 mm column, isocratic 95:5:0.1% water:acetonitrile:TFA, 15 mL/min, elution time 4.5 mins at 210 nm) to give 22 (66.0 mg, 0.25 mmol) as a white solid in 19% yield. Mp. 148-49 °C; δH (400 MHz, CD3\textsubscript{OD}) 3.54-3.64 (3H, m, 3 x CH), 3.78 (1H, dd, J\textsubscript{9.8, 9.8} Hz, CH), 4.13 (1H, ddd, J\textsubscript{4.3, 7.0, 9.8} Hz, CH); δC (100 MHz, CD3\textsubscript{OD}) 46.5, 58.9, 64.5, 73.5, 161.5; δC (125 MHz, D2O) 45.3, 57.0, 62.8, 72.5, 116.6 (CF\textsubscript{3}, q, J\textsubscript{C-F} 329 Hz), 160.1, 163.0 (C, q, J\textsubscript{C-F} 35 Hz). v_{max} 3332, 2976, 2921, 2855, 1738, 1638, 1614, 1361, 1277, 1253, 1158, 1102; MS(CI) 146.1 (100%, [M+H+]; HRMS(CI) C\textsubscript{5}H\textsubscript{12}N\textsubscript{3}O\textsubscript{2} [M+H+], found 146.0920, requires 146.0924.

tert-Butyl (((tert-butoxycarbonyl)amino)(((Z)-5-hydroxypent-3-en-1-yl)amino)methylene)-4-azanecarboxylate 24

Acetate 23\textsuperscript{4} (0.650 g, 1.68 mmol) was dissolved in dry methanol (10 ml), cooled (0 °C) and potassium carbonate (204.0 mg, 1.48 mmol) was added and the mixture stirred for 7 h. The reaction was then filtered through a silica plug, evaporated and the residue purified by chromatography (10-75% EA in PE) to give 24 (0.250 g, 0.728 mmols) in 43% yield as a gum. Rf 0.13 (25:75 EA:PE); δH (400 MHz, CDCl\textsubscript{3}) 1.45 (3H, s, tBu), 1.46 (3H, s, tBu), 2.33 (2H, app q, J\textsubscript{7.0} Hz, CH\textsubscript{2}), 2.63 (1H, br s, OH), 3.44 (2H, app q, J\textsubscript{6.2} Hz, CH\textsubscript{2}), 4.15 (2H, d, J\textsubscript{6.9} Hz, CH\textsubscript{2}), 5.43-5.50 (1H, m, CH), 5.76- 5.82 (1H, m, CH), 8.25 (1H, br s, NH), 11.49 (1H, br s, NH); δC (100 MHz, CDCl\textsubscript{3}) 27.0, 28.1, 28.3, 40.4, 58.2, 79.5, 83.6, 128.2, 132.4, 153.6, 156.0, 163.5; v_{max} 2980, 2933, 1721, 1640, 1618, 1414, 1367, 1329, 1156, 1135; MS(ESI) 344.2 (100 %, [M+H+]); HRMS(CI) C\textsubscript{16}H\textsubscript{30}N\textsubscript{3}O\textsubscript{5} [M+H+], found 344.2180, requires 344.2180.

+/- (R)-1-((S)-2-Iminohexahydropyrimidin-4-yl)ethane-1,2-diol 2,2,2-trifluoroacetate 26

Compound 24 (0.240 g, 0.700 mmol) was epoxidised under the general conditions for 48 hrs to give a crude cyclised product (246 mg) which was dissolved in MeOH (5 mL) to which water (ca. 0.2 mL) was added and the mixture stirred. After 24 h the reaction was evaporated to give crude 25 (215 mg) which was used in the next step without further purification. Compound 25 (215 mg) was dissolved in DCM (5 mL), cooled (0 oC) and trifluoroacetic acid (5 mL) was added and the mixture stirred at rt for 48 h. Evaporation gave crude 26 (216 mg) which was purified by preparative HPLC (ACE 10 C18 250 x 21.8 mm column, isocratic 95:5:0.1% water:acetonitrile:TFA, 15 mL/min, elution time 4.5 mins at 210 nm) to give 26 (29.0 mg, 0.106 mmol) as a gum in 15 % yield. δH (400 MHz, CD3\textsubscript{OD}) 1.72-1.81 (1H, m, CH), 2.03-2.10 (1H, m, CH), 3.26-3.35 (1H, m, CH), 3.45 (1H, ddd, J\textsubscript{5.4, 5.4, 12.6} Hz, CH), 3.46-3.54 (1H, m, 2 x CH) 3.66 (1H, dd, J\textsubscript{4.1, 11.6} Hz, CH), 3.69 (1H, dd, J\textsubscript{4.0, 11.6} Hz, CH); δC (100 MHz, CD3\textsubscript{OD}) 24.2, 38.6, 52.7, 64.6, 74.6 (trifluoroacetate signals not observed); v_{max}
3385, 2982, 2937, 1738, 1254, 1156, 912, 732; **MS(CI)** 160.1 (100%, [M+H+]); **HRMS(CI)** C₆H₁₄N₃O₂ [M+H+], found 160.1078, requires 160.1081.

**Glycosidase assays**¹¹

All enzymes and *para*-nitrophenyl substrates were purchased from Sigma β-galactosidase (bovine liver), α-glucosidase (Bakers yeast), α-mannosidase (Jack bean), β-glucosidase (almond), α-L-fucosidase (human placenta), *N*-acetyl-β-glucosaminidase (Bovine Kidney), Naringinase (*Penicillium decumbens*) and α-galactosidase (green coffee beans). Compounds were assayed at 27 °C in citric acid (0.1 M)/disodium hydrogen phosphate buffers (0.2 M) at the optimum pH for the enzyme. The incubation mixture consisted of enzyme solution (10 µl), an aqueous solution of the substrate (10 µl) appropriate *para*-nitrophenyl substrate (50 µl of a 5 mM solution in buffer). The reactions were stopped by addition of glycine (70 µl, 0.4 M at pH 10.4) during the exponential phase of the reaction. Final absorbances were read at 405 nm using a Versamax microplate reader (Molecular Devices). Assays were carried out in triplicate and the values given are means. Rat intestinal enzyme activities (Sigma rat intestine powder) were also measured using appropriate substrates as above for the enzyme activity measured, the powder (100 mg) was made up in PBS (2 mL) in ice and homogenised and then centrifuged. The supernatant was used as the glycosidase activity source as above.

¶ We had previously² assigned this as a 6-membered product.

**References**


