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Facile triflic acid-catalyzed  $\alpha$ -1,2-*cis*-thio glycosylations: scope and application to the synthesis of S-linked oligosaccharides, glycolipids, sublancin glycopeptides, and T<sub>N</sub>/T<sub>F</sub> antigens

Catalytic triflic acid cleanly knits together glycan donors with thiol acceptors to form glycosyl linkages to peptides, sugars and lipids with excellent  $\alpha$ -selectivity. This back cover art was generated from images downloaded from the Protein Data Bank's NGL viewer. (Rose et. al., *Bioinformatics* **2018**, 34, 3755–3758.)



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# Facile triflic acid-catalyzed $\alpha$ -1,2-*cis*-thio glycosylations: scope and application to the synthesis of *S*-linked oligosaccharides, glycolipids, sublancin glycopeptides, and T<sub>N</sub>/T<sub>F</sub> antigens†

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Studies of *S*-linked glycoconjugates have attracted growing interest because of their enhanced chemical stability and enzymatic resistance over *O*-glycoside counterparts. We here report a facile approach to access  $\alpha$ -1,2-*cis*-*S*-linked glycosides using triflic acid as a catalyst to promote the glycosylation of a series of thiols with *D*-glucosamine, galactosamine, glucose, and galactose electrophiles. This method is broadly applicable for the stereoselective synthesis of *S*-linked glycopeptides, oligosaccharides and glycolipids in high yield and excellent  $\alpha$ -selectivity. Many of the synthetic limitations associated with the preparation of these *S*-linked products are overcome by this catalytic method.

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## Introduction

Protein glycosylation, one of the most ubiquitous post-translational modifications, typically involves the attachment of carbohydrate chains to proteins through the hydroxyl group of serine or threonine (*O*-glycans) or the amido group of asparagine (*N*-glycans).<sup>1–5</sup> The resulting glycoproteins exhibit a diverse array of biological functions such as cell adhesion, protein folding, signal transduction, and immune response.<sup>1–5</sup> However, naturally occurring glycoproteins exist as mixtures of glycoforms, and their isolation as homogeneous species is a complicated process.<sup>6</sup> As such, there is a great demand for methods to efficiently access structurally defined glycoproteins. Recently, replacement of the anomeric oxygen of *O*-linked glycosides with a sulfur atom to generate *S*-linked glycosides has attracted considerable attention because of the enhanced resistance of the latter to chemical and enzymatic hydrolysis.<sup>7,8</sup> In addition, *S*-linked glycosides exhibit similar conformational preferences and equal or even improved biological activities compared to their native *O*-glycoside counterparts.<sup>9–11</sup> In this context, *S*-linked glycan analogs could be utilized as structural mimetics and serve as powerful tools for the biological study of the natural *O*-linked substrates. The recent discovery of *S*-glycosylation, the addition of carbohydrate residues to the sulfur atom of cysteine on bacterial peptides,<sup>12–14</sup> suggests that

naturally existing *S*-linked glycoproteins may be more widespread than was previously thought and may lead to the development of new therapeutics.

Given the significant importance of thiol-containing carbohydrate molecules, methods that enable access to the challenging  $\alpha$ -1,2-*cis* thiol glycosidic linkages are of high synthetic value. Formation of  $\beta$ -1,2-*trans* glycosides can be readily accomplished by employing electrophiles with C(2)-participatory groups.<sup>15</sup> The stereoselective formation of  $\alpha$ -1,2-*cis* glycosides, however, has proven challenging, and a mixture of  $\alpha$ - and  $\beta$ -glycosides is often obtained.<sup>15</sup> A variety of strategies have been reported for the synthesis of mucin-related  $\alpha$ -thiol-containing GalNAc glycopeptide mimetics.<sup>16–24</sup> Representative methods include stereoselective preparation of  $\alpha$ -GalNAc thiols followed by (1) an S<sub>N</sub>2 displacement with  $\beta$ -bromoalanine-containing peptides,<sup>16,17</sup> (2) site-selective conjugation with aziridine-containing peptides,<sup>18,19</sup> or (3) conjugate addition to dehydroalanine-containing peptides.<sup>20</sup> S<sub>N</sub>2 reaction of  $\alpha$ -glycosyl thiols with 4-axial triflate glycosides<sup>21,22</sup> 6-iodinated glycosides,<sup>23–25</sup> enzymatic glycosylation,<sup>26–29</sup> and metal-catalyzed cross coupling,<sup>30,31</sup> have also been reported to generate  $\alpha$ -1,2 *cis* *S*-linked oligosaccharides and glycopeptides. Despite these important advances over the past decades, numerous challenges remain, including the need for highly specialized coupling partners and the multistep preparation of bromoalanine-, aziridine-, and dehydroalanine-containing amino acid residues or peptides.<sup>32</sup> In addition, most of the current methods are limited to specific classes of thiol nucleophiles. To date, there is only one reported method that is applicable for a variety of sulfur nucleophiles, and it uses glycosyl stannane to promote *S*-linked glycoside formation.<sup>31</sup>

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We recently found that triflic acid, released from nickel triflate, can effectively promote the glycosylations of serine/threonine amino acids and hydroxyl groups of carbohydrates with the C(2)-*N-ortho*-(trifluoromethyl)benzylidenamino *N*-phenyl trifluoroacetimidates.<sup>33–36</sup> This catalytic system features several advantages such as mild conditions, short reaction time, good yields and excellent levels of  $\alpha$ -selectivity. However, the question remains whether it will be suited for *S*-glycosylations as Lewis acid-promoted reactions are known to be incompatible with thiol nucleophiles.<sup>37–40</sup> Lewis acid-promoted *S*-glycosylations were underutilized with a few limited examples.<sup>37–40</sup> The reactions generally proceed to provide the coupling products with low yields and require stoichiometric amount of promoter. An inherent issue with the *S*-nucleophiles is their tendency to undergo oxidation to form disulfide and other side products.<sup>38</sup> They also react with the TMSOTf catalyst during the glycosylation process.<sup>40</sup> All those factors make it more challenging to handle *S*-nucleophiles than their *O*-counterparts.

Herein we report a distinct approach to *S*-linked glycosylations: a triflic acid catalyst is shown to enable the facile  $\alpha$ -1,2-*cis* synthesis of thiol-oligosaccharides, glycopeptide of antimicrobial sublancin, *S*-linked tumor-associated T<sub>N</sub>/T<sub>F</sub> antigens, and thiol-glycolipids. This strategy obviates the need for substrate prefunctionalization and can proceed by direct coupling of thiol-containing molecules or cysteine-containing peptides with *N*-phenyl trifluoroacetimidates.

## Results and discussions

To test our hypothesis, we initiated our study by examining the glycosylation of *N*-Cbz cysteine methyl ester **2** with C(2)-*N-ortho*-(trifluoromethyl)benzylidene glucosamine *N*-phenyl trifluoroacetimidate **1** under previously established conditions (Table 1).<sup>36</sup> To our delight, the coupling of **2** with **1** was

successful using 15 mol% nickel triflate, Ni(OTf)<sub>2</sub>, (entry 1). As we expected based on the previously reported conditions,<sup>36</sup> the reaction with 5 mol% triflic acid, TfOH, proceeded to completion within 1 h at 35 °C (entry 2) to afford the desired thiol-linked glycoconjugate **4** in 68% yield with excellent selectivity ( $\alpha$  :  $\beta$  > 20 : 1). This result is consistent with our recently reported mechanism of the triflic acid-catalyzed  $\alpha$ -selective 1,2-*cis* glycosylation with *N*-phenyl trifluoroacetimidate electrophiles.<sup>36</sup> Specifically, triflic acid engages in the activation of electrophile **1** to generate a glycosyl triflate intermediate, which then undergoes equilibration from the stable  $\alpha$ -anomer to the more reactive  $\beta$ -anomer. Subsequent S<sub>N</sub>2-like displacement of the reactive  $\beta$ -anomer of glycosyl triflate by **2** results in the formation of **4** with exclusive  $\alpha$ -configuration.

We observed that while the reaction proceeded to completion faster with use of triflic acid, the glycal elimination product derived from donor **1** was also detected (see Fig. S1† for details). Lowering the reaction temperature (entry 3) and catalyst loading (entry 4) provided a similar outcome (Table 1). To address the problem of **1** from undergoing elimination, the cysteine residue **2** was utilized as the limiting reagent in the presence of 1.5 equiv. of donor **1**. This modification improved the yield to 76% (entry 5). Further increasing the donor **1** to two equivalents gave the desired coupling product **4** in an enhanced 81% yield while maintaining high levels of selectivity (entry 6). Most notably, the glycosylation reached completion within 1 h at 25 °C with use of 5 mol% TfOH to provide **4** with comparable yield and  $\alpha$ -selectivity (entry 7). The cysteine residue **3** with *N*-Fmoc protection, commonly utilized in the solid-phase peptide synthesis (SPPS), also displayed good efficiency (entry 8) to provide the desired glycoconjugate **5** (Table 1) in good yield and  $\alpha$ -selectivity.

With the optimized conditions in hand, we evaluated the scope of the triflic acid-catalyzed *S*-glycosylations (Fig. 1) using

Table 1 Optimization of the reaction conditions<sup>a</sup>

						
Entry	<b>1</b> (equiv.)	<b>2 or 3</b> (equiv.)	Catalyst	Temp. (°C)	Time (h)	<b>4 or 5</b> yield ( $\alpha$ : $\beta$ )
1	1	<b>2</b> (1.5)	15 mol% Ni(OTf) <sub>2</sub>	35	16	<b>4</b> : 66% (>20 : 1)
2	1	<b>2</b> (1.5)	5 mol% TfOH	35	1	<b>4</b> : 64% (>20 : 1)
3	1	<b>2</b> (1.5)	5 mol% TfOH	25	2	<b>4</b> : 68% (>20 : 1)
4	1	<b>2</b> (1.5)	1 mol% TfOH	25	20	<b>4</b> : 67% (>20 : 1)
5	1.5	<b>2</b> (1.0)	3 mol% TfOH	25	3	<b>4</b> : 76% (>20 : 1)
6	2	<b>2</b> (1.0)	3 mol% TfOH	25	3	<b>4</b> : 81% (>20 : 1)
7	2	<b>2</b> (1.0)	5 mol% TfOH	25	1	<b>4</b> : 80% (>20 : 1)
8	2	<b>3</b> (1.0)	5 mol% TfOH	25	1	<b>5</b> : 78% (>20 : 1)

<sup>a</sup> The reaction was conducted with 0.1–0.2 mmol of donor **1**. Yields of the isolated product averaged two runs. The ( $\alpha$ / $\beta$ ) ratios were determined by <sup>1</sup>H NMR analysis.



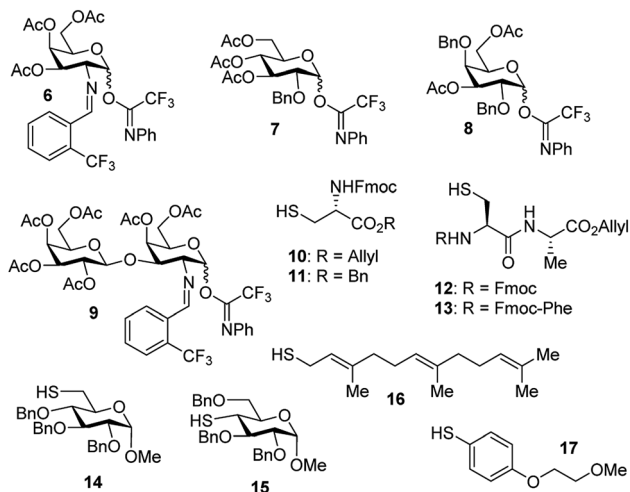


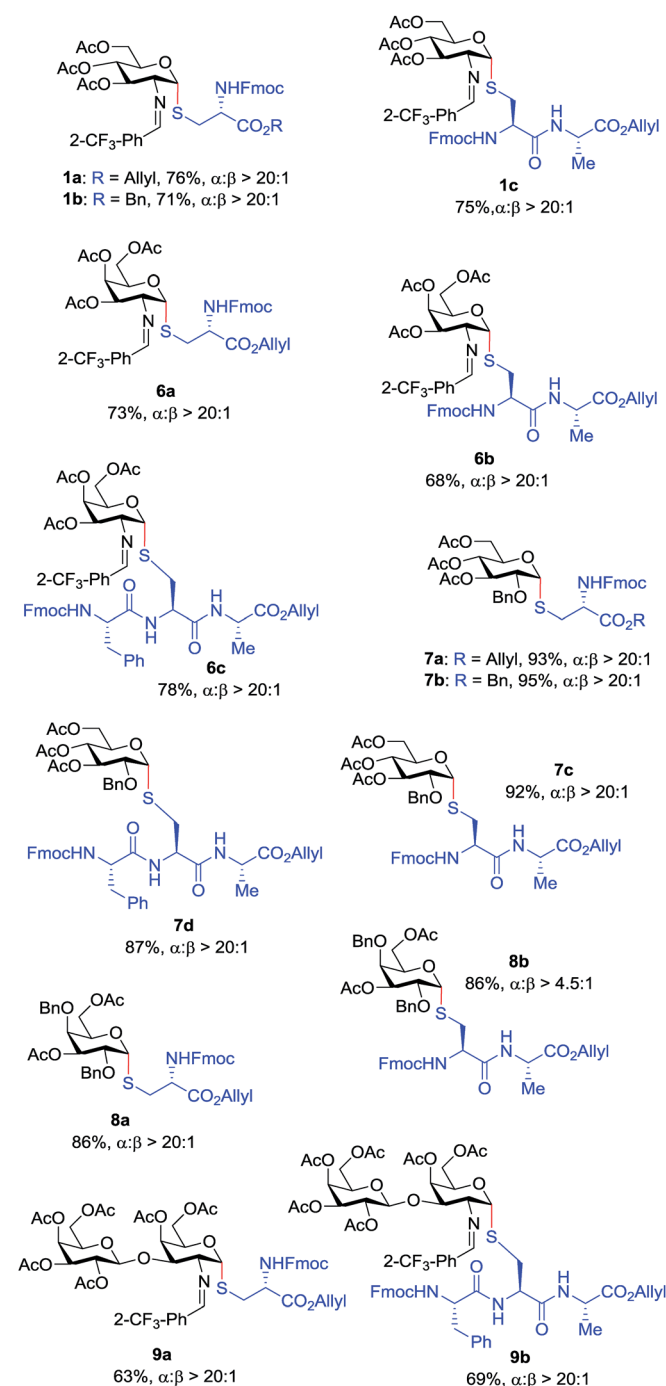
Fig. 1 Carbohydrate donors and thiol-containing acceptors.

glycosyl *N*-phenyl trifluoroacetimidate donors (**1**, **6**–**9**) and thiol-containing molecules (**10**–**17**). Based on our previous study,<sup>36</sup> we anticipated that *N*-phenyl trifluoroacetimidates **1**, **6** and **7** would exhibit high  $\alpha$ -selectivity because their C(2)-*N*-benzylidene and C(2)-benzyl ether can modulate the electronic properties of the anomeric carbon, facilitating isomerization of the glycosyl triflate intermediate. Indeed, both donors **1** and **6** were effectively glycosylated to cysteine amino acids **10** and **11** to provide **1a**, **1b**, and **6a**, respectively, in good yield and with excellent  $\alpha$ -selectivity (Table 2). There are several underlying factors that could influence the stereochemical outcome of the coupling event. To confirm that the  $\alpha$ -selectivity arise from the directing ability of the C(2)-*N*-benzylidene group, we also coupled C(2)-azido donors **18** and **19** with cysteine residue **10** under standard conditions (Scheme 1). The desired products **18a** and **19a** were obtained with poor levels of  $\alpha$ -selectivity ( $\alpha$  :  $\beta$  = 1.6 : 1 to 2 : 1).

These results in Scheme 1 support the importance of the C(2)-*N*-benzylidene group in the triflic acid-catalyzed stereoselective  $\alpha$ -1,2-*cis* *S*-linked glycosylation. Next, we expanded nucleophilic scope from single cysteine amino acid to more complex peptides. Both dipeptide **12** and tripeptide **13** (Fig. 1) performed well under the standard conditions with **1** and **6** to afford glycopeptides **1c**, **6b**, and **6c** (Table 2), presaging the potential utility of this transformation for access *S*-linked glycopeptides of tumor-associated mucin T<sub>N</sub> and T<sub>F</sub> antigens (*vide infra*).<sup>11,44</sup>

In addition to C(2)-*N*-benzylidene electrophiles **1** and **6**, the C(2)-*O*-benzyl protecting group is tolerated. Glucose donor **7** (Table 2) was an effective electrophilic partner, providing the coupling products **7a**–**7d** in excellent yields (87–95%) with exclusive  $\alpha$ -configuration. More importantly, donor **7** does not generate a glycal elimination product. Employing the axial 4-*O*-benzyl protected donor **8** in place of the equatorial 4-*O*-acetyl group (**7**) slightly diminished the  $\alpha$ -selectivity (**8a**:  $\alpha$  :  $\beta$  > 20 : 1, **8b**:  $\alpha$  :  $\beta$  = 4.5 : 1). Nevertheless, this result illustrates the ability of this catalytic system to overturn the inherent bias of *D*-galactose donors whose axial C(4)-*O*-benzyl protecting group

Table 2 Scope with respect to cysteine-containing peptides<sup>a</sup>



<sup>a</sup> All reactions were conducted with donor (2 equiv.), acceptor (1 equiv.) and 5 mol% TfOH in CH<sub>2</sub>Cl<sub>2</sub> at 25 °C for 1 h. Yields of isolated *S*-linked glycopeptides averaged two runs. The ( $\alpha$ / $\beta$ ) ratios were determined by <sup>1</sup>H NMR analysis.

has been reported to favor  $\beta$ -products.<sup>41</sup> The difference in  $\alpha$ -selectivity between the coupling products **8a** and **8b** could be explained by the relative rate for anomerization of the  $\alpha$ -to the  $\beta$ -glycosyl triflate intermediate generated from the reaction of glycosyl electrophile **8** with triflic acid. Since a dipeptide is





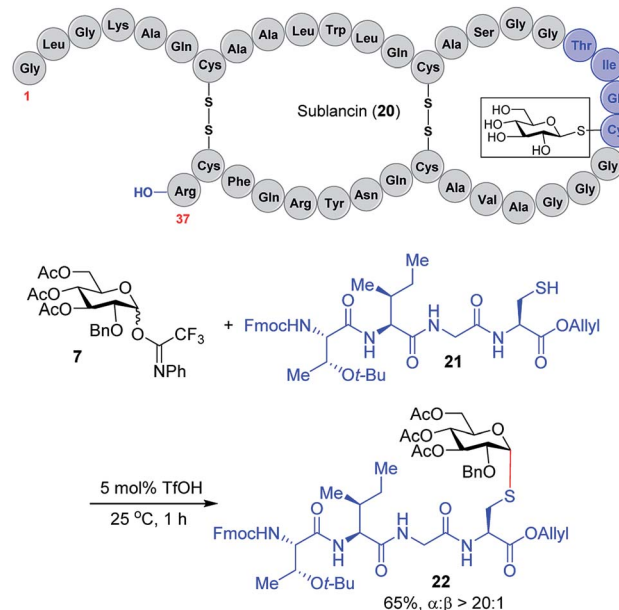
Scheme 1 Glycosylation with C(2)-azido donors **18** and **19**.

a more reactive nucleophile than a cysteine amino acid residue, less time is allowed for anomerization of the  $\alpha$ -triflate to the more reactive  $\beta$ -triflate, resulting in decreasing the  $\alpha$ -selectivity observed in the coupling product **8b**. Finally, disaccharide donor **9**, a carbohydrate motif of T<sub>F</sub> antigen,<sup>42</sup> was readily coupled to provide the corresponding 1,2-*cis* *S*-glycoconjugates **9a** and **9b** (63–69%,  $\alpha : \beta > 20 : 1$ ).

Table 3 Scope with respect to thiol-containing acceptors<sup>a</sup><sup>a</sup> See Table 2.

Inspired by the above discovery, we next examined the scope with respect to nucleophilic coupling partners **14–17**. As illustrated in Table 3, the glycosylations of primary (**14**) and secondary (**15**) thiol acceptors with donors **1**, **6**, and **7** proceeded smoothly to produce the desired *S*-linked disaccharides **14a–c** and **15a–c** in good yields (84–89%) with exclusive  $\alpha$ -selectivity. The *trans,trans*-farnesyl mercaptan **16** was also a suitable nucleophile (**16a, b**), revealing the potential utility of this method for preparation of *S*-linked glycolipids. Recently, Mes-saudi and co-workers reported the Pd-mediated cross coupling of aryl iodides with  $\beta$ -glycosyl thiols to generate *S*-linked glycosides with exclusive  $\beta$ -configuration.<sup>30</sup> For comparison, we examined the coupling efficiency of our method with aryl thiol **17**. To our delight, the reaction compared favorably with excellent  $\alpha$ -stereoselectivity and yield (**17a–c**).

We expect that the triflic acid-catalyzed  $\alpha$ -1,2-*cis* *S*-linked glycosylation method will be particularly useful when applied to the synthesis of bioactive glycopeptides. To establish the potential of a late-stage glycosylation approach, we prepared the tetrapeptide sequence surrounding the  $\beta$ -linked D-glucose unit in sublancin **20** (Scheme 2). This *S*-linked glycosyl unit is essential for antimicrobial activity.<sup>12</sup> SunS, the recently discovered *S*-glycosyl transferase enzyme, is responsible for the unusual glycosylation of cysteine residues with carbohydrates.<sup>12</sup> It has a relaxed substrate specificity and is able to glycosylate other hexose sugars, which has allowed its use in the preparation of sublancin analogs bearing other  $\beta$ -linked glycans.<sup>12,13</sup> However, to the best of our knowledge, the activity of  $\alpha$ -1,2-*cis* *S*-linked sublancin analogs has not been investigated,<sup>10</sup> presumably because of the difficulty of  $\alpha$ -1,2-*cis* *S*-glycosylations. Our current catalytic method would provide an ideal approach for the assembly of such analogs. Accordingly, we investigated the coupling of tetrapeptide **21** with glucose donor **7** in the presence of 5 mol% triflic acid. The

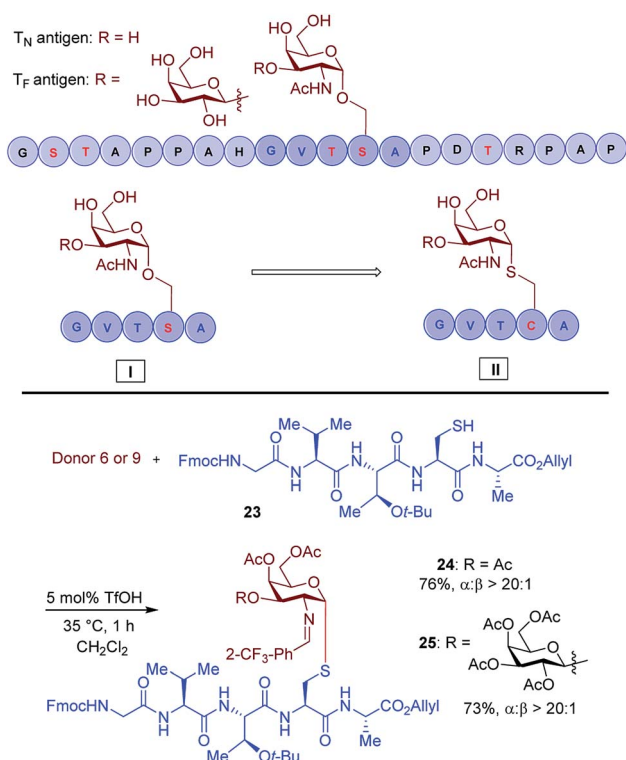


Scheme 2 Synthesis of the sublancin glycopeptide fragment.



glycosylation proceeded to completion within an hour to provide glycopeptide **22** in 65% yield with exclusive  $\alpha$ -selectivity (Scheme 2).

Another important application of this method is the preparation of *S*-linked glycopeptides as analogs of MUC1 type tumor-associated T<sub>N</sub>/T<sub>F</sub> antigens. MUC1 is a glycoprotein that consists of a tandem 20 amino acids repeating unit, with five possible *O*-glycosylation sites (serine or threonine) (Scheme 3).<sup>43</sup> In normal cells, the protein backbone is decorated with complex oligosaccharides, while the glycosylation is incomplete in cancer cells. As such, multiple epitopes such as T<sub>N</sub>/T<sub>F</sub> antigens are exposed to the immune system and can be targeted for the development of antitumor vaccines. A therapeutic vaccine employing multivalent T<sub>N</sub>-antigen clusters and CS4+ T-cell epitopes (MAG-Tn3) has entered to clinical trials.<sup>44</sup> It has been reported that anti-T<sub>N</sub> monoclonal antibodies (mAbs) have a binding preference for T<sub>N</sub>-Ser antigen, and the short MUC1 pentapeptide, GVTSA, is a suitable binding motif for mAbs.<sup>43</sup> Since the *S*-linked T<sub>N</sub> antigen has been proved to enhance the immunogenicity,<sup>41</sup> we sought to prepare *S*-linked T<sub>N</sub>/T<sub>F</sub> antigen mimetics by exchanging the GVTSA sequence (I) for the GVTCA sequence (II) (Scheme 3). Accordingly, we investigated the coupling of GVTCA pentapeptide **23** with both monosaccharide donor **6** and disaccharide donor **9** in the presence of 5 mol% TfOH. The coupling proceeded smoothly at 35 °C for 1 h to provide the corresponding 1,2-*cis* *S*-linked glycopeptides **24** (T<sub>N</sub>) and **25** (T<sub>F</sub>) in 76% and 73% yield, respectively, with exclusive  $\alpha$ -selectivity (Scheme 3).



Scheme 3 Substrate synthesis of *S*-linked T<sub>N</sub> and T<sub>F</sub> glycopeptide fragments.

## Conclusions

In conclusion, we have illustrated the utility of the triflic acid-catalyzed  $\alpha$ -1,2-*cis* thiol glycosylation reaction using stable glycosyl *N*-phenyl trifluoroacetimidates and thiol-containing molecules. This catalytic system obviates the need for substrate prefunctionalization and furnishes a diverse collection of synthetically valuable *S*-linked glycopeptides, oligosaccharides, and glycolipids with excellent  $\alpha$ -selectivity under mild and operationally simple conditions. Notably, the facile nature of this reaction have also successfully applied to the synthesis of *S*-linked glycopeptides of antimicrobial sublancin and tumor-associated mucin T<sub>N</sub>/T<sub>F</sub> antigens. Our future investigations will focus on transforming the current method to automated synthesis for the synthesis of the  $\alpha$ -1,2-*cis* *S*-linked glycosides.

## Conflicts of interest

There are no conflicts to declare.

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## Notes and references

- 1 J. J. Beintema, *J. Mol. Evol.*, 1986, **24**, 118.
- 2 M. Kanagawa and T. Toda, *J. Biochem.*, 2018, **163**, 359.
- 3 N. Kaur and P. Jauhari, *Mol. Cancer Ther.*, 2013, **12**, A27.
- 4 J. Z. Wang, I. GrundkeIqbal and K. Iqbal, *Nat. Med.*, 1996, **2**, 871.
- 5 H. Watarai, R. Nozawa, A. Tokunaga, N. Yuyama, M. Tomas, A. Hinohara, K. Ishizaka and Y. P. Ishii, *Proc. Natl. Acad. Sci. U. S. A.*, 2000, **97**, 13251.
- 6 C. Li and L.-X. Wang, *Chem. Rev.*, 2018, **118**, 8359.
- 7 C. Aydiillo, I. Companon, A. Avenzoza, J. H. Busto, F. Corzana, J. M. Peregrina and M. M. Zurbano, *J. Am. Chem. Soc.*, 2014, **136**, 789.
- 8 C. A. De Leon, P. M. Levine, T. W. Craven and M. R. Pratt, *Biochemistry*, 2017, **56**, 3507.
- 9 A. M. Melo, L. Zhang, E. F. Dockry, A. Petrasca, Y. G. Ghnewa, E. P. Breen, M. E. Morrissey, C. O'Reilly, R. Bruen, A. O'Meara, J. Lysaght, X. M. Zhu and D. G. Doherty, *Glycobiology*, 2018, **28**, 512.
- 10 Z. Amso, S. W. Bisset, S. H. Yang, P. W. R. Harris, T. H. Wright, C. D. Navo, M. L. Patchett, G. E. Norris and M. A. Brimble, *Chem. Sci.*, 2018, **9**, 1686.
- 11 I. Companon, A. Guerreiro, V. Mangini, J. Castro-Lopez, M. Escudero-Casao, A. Avenzoza, J. H. Busto, S. Castillon, J. Jimenez-Barbero, J. L. Asensio, G. Jimenez-Oses, O. Boutureira, J. M. Peregrina, R. Hurtado-Guerrero, R. Fiammengo, G. J. L. Bernardes and F. Corzana, *J. Am. Chem. Soc.*, 2019, **141**, 4063.

- 12 T. J. Oman, J. M. Boettcher, H. Wang, X. N. Okalibe and W. A. van der Donk, *Nat. Chem. Biol.*, 2011, **7**, 78.
- 13 S. Biswas, C. V. Garcia De Gonzalo, L. M. Repka and W. A. van der Donk, *ACS Chem. Biol.*, 2017, **12**, 2965.
- 14 C. Wu, S. Biswas, C. V. Garcia De Gonzalo and W. A. van der Donk, *ACS Infect. Dis.*, 2019, **5**, 454.
- 15 M. J. McKay and H. M. Nguyen, *ACS Catal.*, 2012, **2**, 1563.
- 16 C. F. Liang, M. C. Yan, T. C. Chang and C. C. Lin, *J. Am. Chem. Soc.*, 2009, **131**, 3138.
- 17 X. M. Zhu and R. R. Schmidt, *Chem.–Eur. J.*, 2004, **10**, 875.
- 18 D. P. Galonic, N. D. Ide, W. A. van der Donk and D. Y. Gin, *J. Am. Chem. Soc.*, 2005, **127**, 7359.
- 19 D. P. Galonic, W. A. van der Donk and D. Y. Gin, *J. Am. Chem. Soc.*, 2004, **126**, 12712.
- 20 M. I. Gutierrez-Jimenez, C. Aydillo, C. D. Navo, A. Avenoza, F. Corzana, G. Jimenez-Oses, M. M. Zurbano, J. H. Busto and J. M. Peregrina, *Org. Lett.*, 2016, **18**, 2796.
- 21 L. Lazar, M. Csavas, M. Herczeg, P. Herczegh and A. Borbas, *Org. Lett.*, 2012, **14**, 4650.
- 22 S. Mandal and U. J. Nilsson, *Org. Biomol. Chem.*, 2014, **12**, 4816.
- 23 G. J. L. Bernardes, E. J. Grayson, S. Thompson, J. M. Chalker, J. C. Errey, F. El Oualid, T. D. W. Claridge and B. G. F. Davis, *Angew. Chem., Int. Ed.*, 2008, **47**, 2244–2247.
- 24 X. M. Zhu, T. Haag and R. R. Schmidt, *Org. Biomol. Chem.*, 2004, **2**, 31.
- 25 E. Calce, G. Digilio, V. Menchise, M. Saviano and S. De Luca, *Chem.–Eur. J.*, 2018, **24**, 6231.
- 26 J. R. Rich, A. Szpacenko, M. M. Palcic and D. R. Bundle, *Angew. Chem., Int. Ed.*, 2004, **43**, 613.
- 27 J. R. Rich, W. W. Wakarchuk and D. R. Bundle, *Chem.–Eur. J.*, 2006, **12**, 845.
- 28 G. Tegl, J. Hanson, H. M. Chen, D. H. Kwan, A. G. Santana and S. G. Withers, *Angew. Chem., Int. Ed.*, 2019, **58**, 1632.
- 29 H. Wang, T. J. Oman, R. Zhang, C. V. G. De Gonzalo, Q. Zhang and W. A. van der Donk, *J. Am. Chem. Soc.*, 2014, **136**, 84.
- 30 D. Montoir, M. Amoura, Z. E. Ababsa, T. M. Vishwanatha, E. Yen-Pon, V. Robert, M. Beltramo, V. Piller, M. Alami, V. Aucagne and S. Messaoudi, *Chem. Sci.*, 2018, **9**, 8753.
- 31 F. Zhu, E. Miller, S. Q. Zhang, D. Yi, S. O'Neill, X. Hong and M. A. Walczak, *J. Am. Chem. Soc.*, 2018, **140**, 18140.
- 32 K. Pachamuthu and R. R. Schmidt, *Chem. Rev.*, 2006, **106**, 160.
- 33 E. A. Mensah and H. M. Nguyen, *J. Am. Chem. Soc.*, 2009, **131**, 8778.
- 34 E. A. Mensah, F. Yu and H. M. Nguyen, *J. Am. Chem. Soc.*, 2010, **132**, 14288.
- 35 F. Yu, M. S. McConnell and H. M. Nguyen, *Org. Lett.*, 2015, **17**, 2018.
- 36 E. T. Sletten, Y.-J. Tu, H. B. Schlegel and H. M. Nguyen, *ACS Catal.*, 2019, **9**, 2110.
- 37 C. A. De Leon, G. Lang, M. I. Saavedra and M. R. Pratt, *Org. Lett.*, 2018, **20**, 5032.
- 38 E. Repetto, V. E. Manzano, M. L. Uhrig and O. Varela, *J. Org. Chem.*, 2012, **77**, 253.
- 39 A. Noel, B. Delpéch and D. Crich, *Org. Lett.*, 2012, **14**, 4138.
- 40 G. H. Xin and X. M. Zhu, *Tetrahedron Lett.*, 2012, **53**, 4309.
- 41 S. Chatterjee, S. Moon, F. Hentschel, K. Gilmore and P. H. Seeberger, *J. Am. Chem. Soc.*, 2018, **140**, 11942.
- 42 S. Nath and P. Mukherjee, *Trends Mol. Med.*, 2014, **20**, 332.
- 43 H. Coelho, T. Matsushita, G. Artigas, H. Hinou, F. J. Canada, R. Lo-Man, C. Leclerc, E. J. Cabrita, J. Jimenez-Barbero, S. Nishimura, F. Garcia-Martin and F. Marcelo, *J. Am. Chem. Soc.*, 2015, **137**, 12438.
- 44 R. Lo-Man, S. Vichier-Guerre, R. Perraut, E. Deriaud, V. Huteau, L. BenMohamed, O. M. Diop, P. O. Livingston, S. Bay and C. Leclerc, *Cancer Res.*, 2004, **64**, 4987.

