Title

Cataloging natural sialic acids and other nonulosonic acids (NulOs), and their representation using the Symbol Nomenclature for Glycans.

Journal

Glycobiology, 33(2)

Authors

Frank, Martin
Lütteke, Thomas
Knirel, Yuriy
et al.

Publication Date

2023-03-06

DOI

10.1093/glycob/cwac072

Peer reviewed

Glycobiology, 2023, **33**, 2, 99–103
https://doi.org/10.1093/glycob/cwac072
Advance access publication date 15 January 2023
GlycoForum

Cataloging natural sialic acids and other nonulosonic acids (NulOs), and their representation using the Symbol Nomenclature for Glycans

Amanda L Lewis[1,†,*], Philip Toukach[2], Evan Bolton[3], Xi Chen[4], Martin Frank[5], Thomas Lütteke[6], Yuriy Knirel[7], Ian Schoenhofen[8], Ajit Varki[9], Evgeny Vinogradov[10], Robert J Woods[11], Natasha Zachara[12], Jian Zhang[13], Johannis P Kamerling[14,†,*], Sriram Neelamegham[15,†,*], the SNFG Discussion Group

[1]Department of Obstetrics, Gynecology, and Reproductive Sciences, Glycobiology Research and Training Center, University of California, San Diego, CA 92093, USA, [2]N.D. Zelinsky Institute of Organic Chemistry, Russian Academy of Sciences, Moscow 119991, Russia, [3]National Center for Biotechnology Information, National Library of Medicine, National Institutes of Health, Bethesda, MD 20894, USA, [4]Department of Chemistry, University of California, Davis, CA 95616, USA, [5]Biognos AB, Generatorsgatan 1/Box 8963, 402 74 Göteborg, Sweden, [6]Institute of Veterinary Physiology and Biochemistry, Justus-Liebig-University Giessen, Frankfurter Str. 100, 35392 Giessen, Germany, [7]N.D. Zelinsky Institute of Organic Chemistry, Russian Academy of Sciences, Moscow 119991, Russia, [8]Human Health Therapeutics Research Centre, National Research Council of Canada, Ottawa, ON K1A OR6, Canada, [9]Department of Medicine and Cellular & Molecular Medicine, Glycobiology Research and Training Center, University of California, San Diego, CA 92093, USA, [10]Human Health Therapeutics Research Centre, National Research Council of Canada, Ottawa, ON K1A OR6, Canada, [11]Complex Carbohydrate Research Center, University of Georgia, Athens, GA 30602, USA, [12]Department of Biological Chemistry, Johns Hopkins University School of Medicine, Baltimore, MD 21205, USA, [13]National Center for Biotechnology Information, National Library of Medicine, National Institutes of Health, Bethesda, MD 20894, USA, [14]Bijvoet Center, Utrecht University, 3584 CH Utrecht, The Netherlands, [15]Department of Chemical & Biological Engineering, Biomedical Engineering and Medicine, State University of New York, Buffalo, NY 14260, USA

*Corresponding authors: Sriram Neelamegham, 906 Furnas Hall, State University of New York, Buffalo, NY 14260-4200, USA. Email: neel@buffalo.edu; Johannis P. Kamerling, Bijvoet Center, Utrecht University, Utrecht, The Netherlands. Email: j.p.kamerling@uu.nl; Amanda L. Lewis, Glycobiology Research and Training Center, University of California, San Diego, CA, USA. Email: a1lewis@health.ucsd.edu

[†]Co-corresponding authors

Nonulosonic acids or non-2-ulosonic acids (NulOs) are an ancient family of 2-ketoaldonic acids (α-ketoaldonic acids) with a 9-carbon backbone. In nature, these monosaccharides occur either in a 3-deoxy form (referred to as "sialic acids") or in a 3,9-dideoxy "sialic-acid-like" form. The former sialic acids are most common in the deuterostome lineage, including vertebrates, and mimicked by some of their pathogens. The latter sialic-acid-like molecules are found in bacteria and archaea. NulOs are often prominently positioned at the outermost tips of cell surface glycans, and have many key roles in evolution, biology and disease. The diversity of stereochemistry and structural modifications among the NulOs contributes to more than 90 sialic acid forms and 50 sialic-acid-like variants described thus far in nature. This paper reports the curation of these diverse naturally occurring NulOs at the NCBI sialic acid page (https://www.ncbi.nlm.nih.gov/glycans/sialic.html) as part of the NCBI-Glycans initiative. This includes external links to relevant Carbohydrate Structure Databases. As the amino and hydroxyl groups of these monosaccharides are extensively derivatized by various substituents in nature, the Symbol Nomenclature For Glycans (SNFG) rules have been expanded to represent this natural diversity. These developments help illustrate the natural diversity of sialic acids and related NulOs, and enable their systematic representation in publications and online resources.

Key words: glycans; NulO; nonulosonic acid; sialic acid; symbol nomenclature.

A catalog of naturally occurring sialic acids and sialic-acid-like monosaccharides

The "sialic acid" and "sialic-acid-like" subclasses of monosaccharides belong to a larger superfamily of organic compounds called the non-2-ulosonic acids, nonulosonic acids (2-ketoaldonic acids; α-ketoaldonic acids), or "NulOs" note-1.

These negatively charged monosaccharides commonly occur as terminal and sometimes as internal residues in glycoconjugates (e.g. glycoproteins, glycolipids, lipooligo/lipopolysaccharides, capsular, and tissue polysialic acids) and carbohydrates (e.g. oligosaccharides, exopolysaccharides). Due to their terminal presentation on cell surface glycans, they facilitate numerous key biological functions related to cellular recognition, cell adhesion, communication/signaling, control of glycoconjugate half-life in circulation, tumor growth and metastasis, and developmental programming. NulOs also have key roles in immune regulation, as well as host interactions with viruses, bacterial pathogens, and the microbiota, including commensals, symbionts, and opportunistic pathogens.

The NulOs display expansive natural diversity. This is largely due to variations in their stereochemistry,

[1] Note: Following the 1996 IUPAC/IUBMB Nomenclature of Carbohydrates Recommendations (McNaught, A.D. 1997) on ketoaldoses (aldosuloses) (chapter *2-Carb-12*), the locant of the ketonic carbonyl group is given as an infix before "ulose" unless it is 2 (the aldehydic carbonyl group is numbered 1). Although, based on this recommendation, it is not necessary to add "2" in case of 2-uloses, for the sake of clarity "2" is frequently retained. A similar situation holds for ketoaldonic acids (aldulosonic acids) (chapter *2-Carb-21*). Although not specified in *2-Carb-21*, it is consistent with *2-Carb-12* to say that the locant of the ketonic carbonyl group is given as an infix before "ulosonic acid" unless it is 2. Then, "3-deoxy-nonulosonic acids" and "3,9-dideoxy-nonulosonic acids" are simplified names of "3-deoxy-non-2-ulosonic acids" and "3,9-dideoxy-non-2-ulosonic acids," respectively.

Received: July 1, 2022. **Revised:** September 14, 2022. **Accepted:** October 18, 2022

derivatization of hydroxyl and amino groups, and internal dehydration. Recently, as part of the NCBI-Glycans initiative, we reviewed the diversity of the NulOs and presented them at the "NCBI-sialic acid page": https://www.ncbi.nlm.nih.gov/glycans/sialic.html (**Supplementary Tables I** and **II**). This effort extends the curation work by Schauer and Kamerling (Schauer and Kamerling 2018) by performing extensive additional literature review, including a survey of supplemental NulOs reported at the carbohydrate structure database: http://csdb.glycoscience.ru/ (Toukach and Egorova 2016). As the facilities in the community-curated Symbol Nomenclature For Glycans [SNFG, (Varki et al. 2015, Neelamegham et al. 2019, Appendix-1B 2022)] were inadequate for the symbolic description of NulO diversity, the SNFG rules and usage were expanded. The expanded description of NulO diversity is now presented at the NCBI-sialic acid page, including the SNFG depiction of the NulOs, cross-referenced with primary literature citations and supporting database links, when available.

Two groups of NulOs are presented at the NCBI-sialic acid page, the 3-deoxy NulOs termed "sialic acids" (Fig. 1a–d), and the 3,9-dideoxy NulOs or "sialic-acid-like" entities (Fig. 1e–j). Here, Fig. 1a–d represents the four primary types of the 3-deoxy-non-2-ulosonic acids (sialic acids): neuraminic acid (Neu), *N*-acetylneuraminic acid (Neu5Ac), *N*-glycolylneuraminic acid (Neu5Gc), and ketodeoxynononic acid (Kdn). A survey of over 90 variants of sialic acids is presented in Table 1 of the NCBI sialic acid page (also listed in **Supplementary Table I**). Figure 1e–j presents the 3,9-dideoxy-non-2-ulosonic acids in 6 subclasses corresponding to 6 stereoisomers: pseudaminic acid (Pse), legionaminic acid (Leg), 4-*epi*-legionaminic acid (4eLeg), 8-*epi*-legionaminic acid (8eLeg), acinetaminic acid (Aci), and 8-*epi*-acinetaminic acid (8eAci). A survey of over 50 known structures of naturally occurring 5,7-diamino-3,5,7,9-tetradeoxy-non-2-ulosonic acid derivatives, together with some related 9-deoxy-non-2-ulosonic acids, is presented in Table 2 of the NCBI-sialic acid page (also listed in **Supplementary Table II**). Note that the drawings of the glycerol side chains for both the 3-deoxy and 3,9-dideoxy NulOs in Fig. 1 differ from the 1996 IUPAC/IUBMB recommendation (McNaught 1997), as they are based on more recent conformation studies.

Expansion of the snfg for describing the nonulosonic acids and related substituents

The SNFG is a community curated, living document that enables a simplified representation of glycan structures. The most recent version of the SNFG is available at the "NCBI-SNFG page": https://www.ncbi.nlm.nih.gov/glycans/snfg.html. To systematize and render sialic acid-containing glycans and portray their biology, refinements have been made to the SNFG in consultation with a working group of investigators in this field. To this end, the row dedicated to "deoxynonulosonate" (i.e. sialic acids) and "dideoxynonulosonate" (i.e. the sialic-acid-like NulOs that have only been found in prokaryotes so far) in the main table at the NCBI-SNFG page have been renamed "3-deoxy-nonulosonic acids" and "3,9-dideoxy-nonulosonic acids," respectively, as this is more precise. The heading of footnote 6 (previously "sialic acid") has also been updated to be more inclusive of the larger family of nonulosonic acids.

Table 1. SNFG substituent list and abbreviations.[a]

Abbreviation	Substituent name
Ac	acetyl
Ala	D-alanyl
Ala2Ac	*N*-acetyl-D-alanyl
Am	*N*-acetimidoyl
AmMe	*N*-(*N*-methyl-acetimidoyl)
$AmMe_2$	*N*-(*N*,*N*-dimethyl-acetimidoyl)
Fo	formyl
Gc	glycolyl
Gln2Ac	*N*-acetyl-glutaminyl
5Glu2Me	*N*-methyl-5-glutamyl
Gly	glycyl
Gr	glyceryl
$Gr2,3Me_2$	2,3-di-*O*-methyl-glyceryl
4Hb	4-hydroxybutyryl
3,4Hb	3,4-dihydroxybutyryl
3_RHb	(*R*)-3-hydroxybutyryl
3_SHb	(*S*)-3-hydroxybutyryl
Lt	lactyl
Me	methyl
N	amino
NAc	*N*-acetyl
P	phosphate
Py	pyruvyl
Pyr	1-carboxyethylidene
S	sulfate
Tau	tauryl

[a]If multiple substituents are attached to a single monosaccharide, in the SNFG rendering, the substituent abbreviations appear in alphabetical order.

The colors used to depict the nonulosonic acids in the SNFG are partly based on history in the field, and partially based on the stereochemistry of the monosaccharides. In this regard, all residues in the sialic acid row have identical stereochemistry. Here, the different colored diamonds reflect the primary substituents at C5: Neu, brown; Neu5Ac, purple; Neu5Gc, light blue; and Kdn, green. The red diamond in the SNFG is present for historical reasons and can still be used to depict any type of sialic acid (coded "Sia"). While the white diamond can be used for the same purpose, the red color aims to stress the biological importance of this terminal modification. As a more recent addition to the SNFG, the colors of the flat diamonds (the "3,9-dideoxy-nonulosonic acids") are based on the stereochemistry, consistent with representations of the other monosaccharide classes. In this regard, Pse is green due to its *manno*-configuration, as conveyed in its full chemical name. Leg and 8eLeg are yellow due to their *galacto*-configuration; these monosaccharides only differ in their "glycerol" part. 4eLeg is light blue due to its *talo*-configuration, and Aci and 8eAci share the pink color due to their *altro*-configuration.

NulOs and a number of other monosaccharides contain modifications to the base structure in the form of lactam, lactone, anhydro, and didehydro (Fig. 2). The depiction of such fully defined compounds was previously not possible using the SNFG, and thus, these entities were commonly displayed as white pentagons with footnotes providing additional information about the structure. This shortcoming is addressed in the revised SNFG, by allowing two letter phonetic codes within the monosaccharide symbol: "*am*" for lactam, "*on*" for lactone, "*an*" for anhydro, and "*en*" for didehydro (revised footnote 4 at the NCBI-SNFG page). These new facilities are extensions of previous SNFG rules that

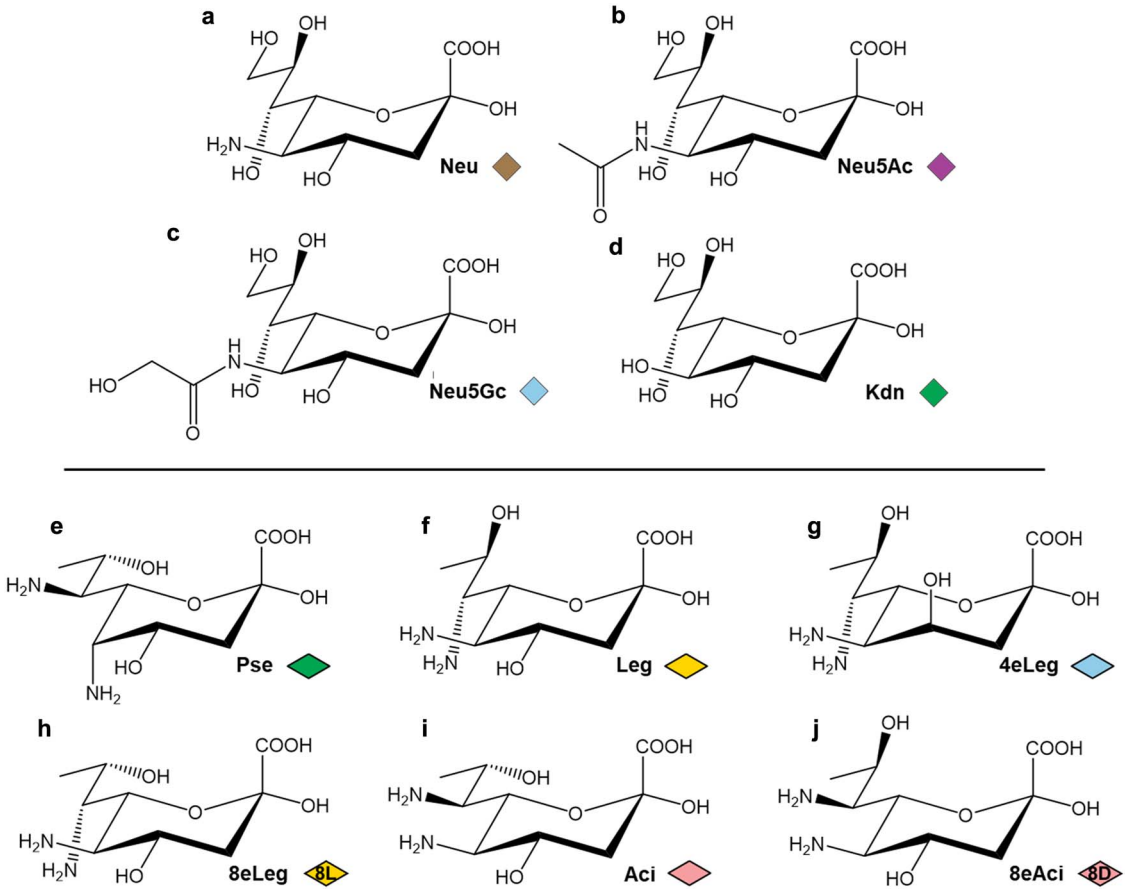

Fig. 1. The non-2-ulosonic acids (NulOs). a–d) The 3-deoxy-non-2-ulosonic acids (sialic acids): The parent compound in this class is a) neuraminic acid (Neu, 5-amino-3,5-dideoxy-D-*glycero*-D-*galacto*-non-2-ulosonic acid). The presence of acetamido and hydroxyacetamido substituents at C5 results in b) *N*-acetylneuraminic acid (Neu5Ac, 5-acetamido-3,5-dideoxy-D-*glycero*-D-*galacto*-non-2-ulosonic acid), and c) *N*-glycolylneuraminic acid (Neu5Gc, 3,5-dideoxy-5-hydroxyacetamido-D-*glycero*-D-*galacto*-non-2-ulosonic acid), respectively. Replacement of the C5 amine with hydroxyl results in d) ketodeoxynononic acid (Kdn, 3-deoxy-D-*glycero*-D-*galacto*-non-2-ulosonic acid). e–j) The 3,9-dideoxy-non-2-ulosonic acids (sialic-acid-like subclass compounds). This family includes six subclasses of compounds: e) pseudaminic acid (Pse, 5,7-diamino-3,5,7,9-tetradeoxy-L-*glycero*-L-*manno*-non-2-ulosonic acid), f) legionaminic acid (Leg, 5,7-diamino-3,5,7,9-tetradeoxy-D-*glycero*-D-*galacto*-non-2-ulosonic acid), G) 4-*epi*-legionaminic acid (4eLeg, 5,7-diamino-3,5,7,9-tetradeoxy-D-*glycero*-D-*talo*-non-2-ulosonic acid), h) 8-*epi*-legionaminic acid (8eLeg, 5,7-diamino-3,5,7,9-tetradeoxy-L-*glycero*-D-*galacto*-non-2-ulosonic acid), i) acinetaminic acid (Aci, 5,7-diamino-3,5,7,9-tetradeoxy-L-*glycero*-L-*altro*-non-2-ulosonic acid), and j) 8-*epi*-acinetaminic acid (8eAci, 5,7-diamino-3,5,7,9-tetradeoxy-D-*glycero*-L-*altro*-non-2-ulosonic acid). The $^{2}C_{5}$ chair conformations of Neu, Neu5Ac, Neu5Gc, Kdn, Leg, 4eLeg, and 8eLeg are presented in the α-anomeric configuration and the $^{2}C_{5}$ chair conformations of Pse, Aci, and 8eAci are in the β-anomeric configuration. Note that in all structures shown here, the COOH group at C2 has an axial orientation. All SNFG figures in this report were rendered using DrawGlycan-SNFG (Cheng et al. 2017).

used "*f*" to depict furanose rings, "*o*" for alditols, and "*a*" for open-chain monosaccharides at the free reducing end. The default carbon positions for these modifications in sialic acids are at C1 and C5 for *am* (1-5*am*), C1 and C7 for *on* (1-7*on*), C2 and C7 for *an* (2-7*an*), and C2 and C3 for *en* (2-3*en*). As these variations are in the base monosaccharide structures, when presented in text form, these are specified immediately following the monosaccharide and prior to any substituent (e.g. "Neu2en5Ac" rather than "Neu5Ac2en," and "Neu2,7an5Ac" rather than "Neu5Ac2,7an") (Reuter and Schauer 1988). Indeed, additional base monosaccharide structure modifications are possible (e.g. 4-8*an*), and such departures from the default assignment may be specified in figure footnotes or legends.

N/*O*-Acetyl, *O*-phosphate, and *N*/*O*-sulfate are common substituents that are present on a variety of monosaccharides. While a limited catalog of such substituents was previously supported by the SNFG using text either above or below the colored symbol, this list and the rules for their usage have been vastly expanded to accommodate the nonulosonic acids (revised footnote 7 at the NCBI-SNFG page). The expanded list of substituents in this SNFG revision is listed in Table 1 of this report, with exact chemical drawings displayed at the main NCBI-SNFG page. When arriving at this list, we were guided by IUPAC conventions but also allowed common names in order to keep with previous usage in the field and enhance human readability. Substituent abbreviations were kept purposefully short to save space in figures, and numbers were avoided to reduce confusion with numbers otherwise used to indicate substituent linkage position. If, as in some situations, numbers are unavoidable in the substituent name, these are enclosed within parentheses to avoid confusion with attachment site (example in Fig. 3a). If multiple substituents are attached to a single monosaccharide, these appear in alphabetical order based on the abbreviations listed in Table 1 (example in Fig. 3b). In this regard, the SNFG relies on alphabetical ordering of substituent abbreviations in contrast to IUPAC, which uses the full name to

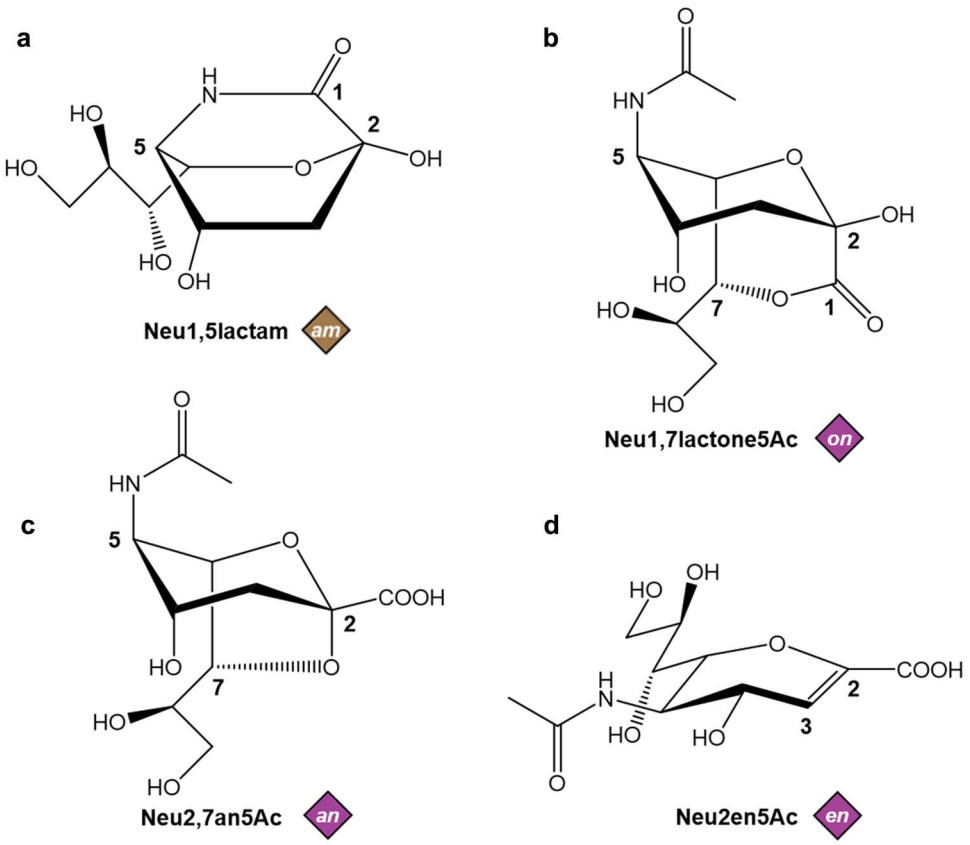

Fig. 2. Modifications to the monosaccharide base structure. The complete chemical structures and associated SNFG representations of a) lactam (Neu1,5lactam), b) lactone (Neu1,7lactone5Ac), c) anhydro (Neu2,7an5Ac), and d) didehydro (Neu2en5Ac) sialic acids.

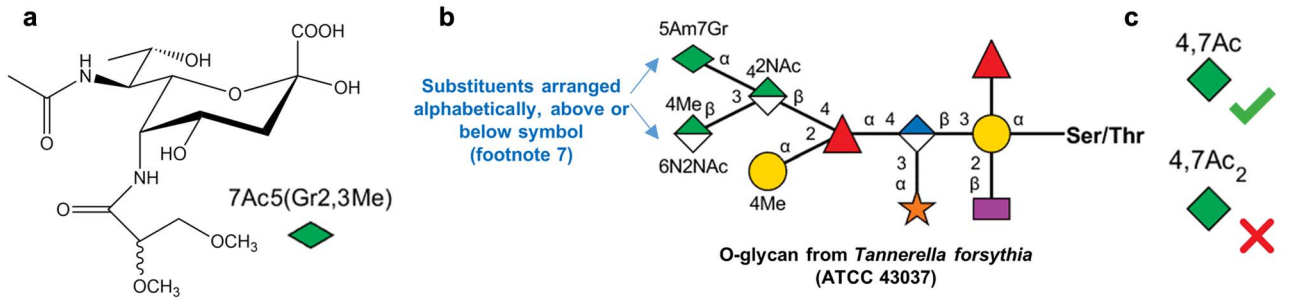

Fig. 3. Selected examples of new SNFG rules. a) 7-*N*-acetyl-5-*N*-(2,3-di-*O*-methyl-glyceryl)-pseudaminic acid [Pse7Ac5(Gr2,3Me$_2$)], b) O-glycan from *Tannerella forsythia* (Tomek et al. 2018), with the terminal acids: 5-*N*-acetimidoyl-7-*N*-glyceryl-pseudaminic acid (Pse5Am7Gr) and 4-*O*-methyl-*N*-acetylmannosaminuronamide (ManA4Me6N2NAc). Note the use of "2NAc" to indicate C2 location of *N*-acetyl group, as this is not implicit in the base ManA symbol. c) Correct (top) and incorrect (bottom) representation of 4,7-di-*O*-acetyl-2-keto-3-deoxy-nononic acid [Kdn4,7Ac$_2$].

determine alphabetic position. Thus, acetimidoyl (Am) appears before acetyl (Ac) in IUPAC, whereas Ac precedes Am in the SNFG. Additionally, if the same modification appears at multiple carbon locations, this is presented in numerical order. As space is limited in the SNFG renderings, subscripts have been dropped (e.g. Kdn4,7Ac$_2$ is depicted as a green diamond with 4,7Ac, rather than 4,7Ac$_2$) (Fig. 3c). Additional substituents not in Table 1 can be included in the SNFG using symbols (such as ∗, †, or ‡) above the SNFG monosaccharide and associated text footnotes describing substituents. Overall, the above usages are mostly consistent with IUPAC/IUBMB recommendations (McNaught 1997), though not all substituents that are part of the SNFG are described by IUPAC.

Some carbons of the base NulO symbols bear amino groups, while others bear hydroxyl functions. For example, in Fig. 1, amino groups are noted at the 5-position of neuraminic acid, and at the 5 and 7 positions of pseudaminic acid. The attachment of substituents to these amino residues would result in N-linked addition by default, while the attachment of substituents to the hydroxyl groups on the base monosaccharide structure would result in O-linked substituents (footnote 8 at the NCBI-SNFG page). Thus, Neu4,5Ac$_2$8Me indicates O-acetylation at C4 of Neu (neuraminic acid), N-acetylation at C5, and O-methylation at C8. Furthermore, substituents may be concatenated to indicate multiple modifications, with position indicated for the first substituent, e.g. "Neu5(Gc2Ac)" depicting the C5 modification of Neu by a glycolyl group

which is further modified by O-acetylation at C2 of the glycolyl substituent. If a given string concatenation results in a non-unique chemical description, the exact chemical structure should be provided using IUPAC/IUBMB recommendations. Finally, the presence of variable amounts of substituents can be indicated using the ±symbol or by indicating % presence, if known (e.g. "60% 3Ac" to indicate presence of 3Ac on 60% of a residue or repeating unit). Besides sialic acids, such variable substituents can also aid the description of other carbohydrate modifications, e.g. the sulfation of galactose, *N*-acetylgalactosamine, and *N*-acetylglucosamine on various glycosaminoglycans.

Conclusion

The revised SNFG guidelines presented in this paper allow the symbolic description of most currently identified nonulosonic acids. However, some newer entities such as fusaminic acid are still depicted as generic 3,9-dideoxy-nonulosonic acids, i.e. generic white flattened diamond (Table 2, NCBI-sialic acid page). In this regard, we await a more complete description of this and other related NulOs before further expanding the SNFG. In closing, the strength of the SNFG is its simplicity, wide-applicability, parsimony, and ability to incorporate previous biochemical knowledge such as the IUPAC/IUBMB recommendations. The overarching philosophy is not to describe all nuances in the literature, but rather to simplify the exchange of data in the scientific community, lower the barrier for new entrants in the Glycoscience field, and to serve as a bridge for integrating glycan-related knowledge into the NCBI and other biomedical databases and online resources.

Authors' contributions

Other members of the SNFG Discussion Group: Alan Darvill, University of Georgia, USA; Anne Dell, Imperial College London, UK; Bernard Henrissat, Technical University of Denmark, Denmark; Carolyn Bertozzi, Stanford University, USA; Frederique Lisacek, Swiss Institute of Bioinformatics (SIB), Switzerland; Gerald Hart, University of Georgia, USA; Hisashi Narimatsu, Research Center of Medical Glycoscience, Japan; Hudson Freeze, Sanford-Burnham-Prebys Research Institute, USA; Issaku Yamada, The Noguchi Institute, Japan; James Paulson, Scripps Research Institute, USA; Jamey Marth, University of California Santa Barbara, USA; JFG Vliegenthart, Bijvoet Center, Netherlands; Kiyoko F. Aoki-Kinoshita, Soka University, Japan; Marilynn Etzler, UC Davis, USA; Markus Aebi, ETH Zürich, Switzerland; Matthew Campbell, Institute for Glycomics, Griffith University, Australia; Michael Tiemeyer, University of Georgia, Complex Carbohydrate Research Center, USA; Minoru Kanehisa, Kyoto University, Japan; Naoyuki Taniguchi, Riken Global Research Cluster, Japan; Nathan Edwards, Georgetown University, USA; Nicolle Packer, Macquarie University, Australia; Pamela Stanley, Albert Einstein College of Medicine, USA; Pauline Rudd, National Institute for Bioprocessing Research & Training, UK; Peter Seeberger, Max-Planck-Institute of Colloids and Interfaces, Germany; Raja Mazumder, The George Washington University, USA; Rene Ranzinger, University of Georgia, USA; Richard Cummings, Harvard Medical School, USA; Roger Sayle, NextMove Software, UK; Ronald Schnaar, Johns Hopkins University School of Medicine, USA; Serge Perez, French National Centre for Scientific Research, France; Stuart Kornfeld, Washington University in St. Louis, USA; Taroh Kinoshita, Osaka University, Japan; William York, University of Georgia, USA.

Supplementary material

Supplementary material is available at *Glycobiology* Journal online.

Acknowledgments

This is an international, community-driven project. This report is dedicated in the memory of Prof. Roland Schauer and his contributions to our understanding of sialic acids.

Funding

This works is not supported by any explicit research grant. However, some of the individuals who volunteer their time as members of the SNFG Discussion Group have received grant support from national funding agencies including, but not limited to, the US National Institutes of Health and the Russian Science Foundation. The work of EB and JZ was supported by the National Center for Biotechnology Information of the National Library of Medicine (NLM), National Institutes of Health.

Conflict of interest statement

None declared. All data are incorporated into the article and its online supplementary material.

References

Appendix-1B. 2022. www.ncbi.nlm.nih.gov/books/NBK579974/. In: Varki A, et al. editor. *Essentials of Glycobiology*. 4th Edition. Cold Spring Harbor (NY): Cold Spring Harbor Laboratory Press.

Cheng K, Zhou Y, Neelamegham S. DrawGlycan-SNFG: a robust tool to render glycans and glycopeptides with fragmentation information. *Glycobiology*. 2017:**27**:200–205.

McNaught AD. International Union of Pure and Applied Chemistry and International Union of Biochemistry and Molecular Biology. Joint Commission on Biochemical Nomenclature. *Nomenclature of carbohydrates Carbohydr Res*. 1997:**297**:1–92.

Neelamegham S, Aoki-Kinoshita K, Bolton E, Frank M, Lisacek F, Lütteke T, O'Boyle N, Packer NH, Stanley P, Toukach P et al. Updates to the Symbol Nomenclature for Glycans guidelines. *Glycobiology*. 2019:**29**:620–624.

Reuter G, Schauer R. Suggestions on the nomenclature of sialic acids. *Glycoconj J*. 1988:**5**:133–135.

Schauer R, Kamerling JP. Exploration of the Sialic Acid World. *Adv Carbohydr Chem Biochem*. 2018:**75**:1–213.

Tomek MB, Maresch D, Windwarder M, Friedrich V, Janesch B, Fuchs K, Neumann L, Nimeth I, Zwickl NF, Dohm JC et al. A General Protein O-Glycosylation Gene Cluster Encodes the Species-Specific Glycan of the Oral Pathogen *Tannerella forsythia*: O-Glycan Biosynthesis and Immunological Implications. *Front Microbiol*. 2018:**9**:2008.

Toukach PV, Egorova KS. Carbohydrate structure database merged from bacterial, archaeal, plant and fungal parts. *Nucleic Acids Res*. 2016:**44**:D1229–D1236.

Varki A, Cummings RD, Aebi M, Packer NH, Seeberger PH, Esko JD, Stanley P, Hart G, Darvill A, Kinoshita T et al. Symbol Nomenclature for Graphical Representations of Glycans. *Glycobiology*. 2015:**25**:1323–1324.