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Metabolic Labeling of Sialic Acids in Living Animals with Alkynyl Sugars

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Sialic acids, a family of monosaccharides widely distributed in higher eukaryotes and certain bacteria, are determinants of many functional glycans that play central roles in numerous physiological and pathological processes.[1] For example, the sialic acid-containing epitope Sia α 2–6Gal serves as the cellular receptor for human influenza-A and -B viruses during infection,[2] and linear homopolymers of sialic acids, known as polysialic acid (PSA), modulate neuronal synapse formation in mammalian development.[3] The expression of sialoglycoconjugates, such as sialyl Lewis x, sialyl Tn (STn), and PSA, is also a common feature shared by numerous cancers.[4] Interestingly, upregulation of these sialosides is strongly correlated with the transformed phenotype of many cancers.[5,6] For example, STn, a mucin-associated disaccharide, is not normally found in healthy tissues but is expressed by malignant tumors, including those of the pancreas and breast.[7,8] In addition, a strong correlation between the level of cell surface sialic acids and metastatic potential has been observed in several different tumor types.[9] Thus, as cancer cells generally display higher levels of sialic acid than their nonmalignant counterparts, sialylated glycoconjugates, collectively termed the “sialome”, constitute attractive targets in the search for novel cancer biomarkers.

A variety of methods has been reported for the enrichment and identification of sialylated glycoproteins from bodily fluids or cell lysates. For example, affinity chromatography using

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sialic acid-specific lectins[10–12] or selective periodate oxidation of sialic acids followed by hydrazide capture[13] can provide glycoprotein samples that are enriched for sialylated species. These methods have been used for comparative analysis of the steady-state abundances of sialylated glycoproteins in serum from cancer patients and healthy subjects. [1]

A complementary method that we have developed involves metabolic labeling of sialylated glycoproteins by treating cells or living animals with peracetylated analogs of *N*-acetylmannosamine (ManNAc) bearing chemical reporter groups such as the azide (i.e., peracetylated *N*-azidoacetylmannosamine, Ac₄ManNAz).[15,16] Ac₄ManNAz is enzymatically deacetylated in the cytosol and then metabolically converted to the corresponding *N*-azidoacetyl sialic acid (SiaNAz), which is subsequently incorporated into sialoglycoconjugates.[15,17] Once presented on the cell surface, the azide-labeled sialylated glycans can be visualized or captured for glycoproteomic analysis with a variety of reagents[18], including Staudinger ligation phosphines[15], terminal alkynes along with reagents for Cu(I)-catalyzed azide-alkyne cycloaddition (CuAAC)[19,20], or strained alkynes.[21] Wong and coworkers reversed the polarity of the reagents, using an alkynyl ManNAc derivative for metabolic labeling of cultured cells and CuAAC-mediated reaction with an azide-functionalized probe for capture of sialylated glycoproteins.[22,23]

The metabolic/chemical labeling method holds several advantages over previous approaches to sialylated glycoprotein analysis. First, metabolic labeling selects for those glycoproteins that are biosynthesized at high levels, irrespective of their steady-state abundance. Thus, metabolic labeling may reveal novel sialylated biomarkers that are turned over rapidly and therefore missed by steady-state labeling methods. Second, metabolic labeling can be performed in live animals[16], permitting the selective tagging of sialylated glycoconjugates within their native tissue environments. However, the efficiency of sialic acid labeling using Ac₄ManNAz is fairly low *in vivo*. Mouse heart tissue glycoproteins incorporate SiaNAz at ~3% of total sialic acid, and the azidosugar is undetectable in some organs that are known to possess sialylated glycoconjugates.[16]

The efficiency of sialic acid biosynthesis is very sensitive to the *N*-acyl structure of unnatural ManNAc analogs.[25,26] Analogues with long or branched *N*-acyl chains are poor substrates for the biosynthetic enzymes, while those containing short, linear side chains are better tolerated.[26] Thus, we were curious how the alkynyl ManNAc analog reported by Wong and coworkers[23] would fare in live animal metabolic labeling studies compared to ManNAz. Toward this goal, we synthesized peracetylated *N*-(4-pentynoyl) mannosamine (Ac₄ManNAI, Figure 1) and confirmed its metabolic conversion to the corresponding sialic acid (SiaNAI) in cultured cells. Jurkat cells, a human T lymphoma cell line, were cultured with 50 μM Ac₄ManNAI for three days, after which their lysates were reacted with an azido biotin derivative (biotin-azide, Figure 1)[27] using standard CuAAC conditions.[28] Western blot analysis showed significant glycoprotein labeling in lysates from cells treated with Ac₄ManNAI but no detectable labeling in lysates from untreated cells (Figure 2).

We confirmed the presence of SiaNAI within these cellular glycans by performing sialic acid compositional analysis using established protocols (see Supporting Information for description of methods).[24] As shown in Table 1, we compared the efficiencies of metabolic conversion of Ac₄ManNAI and Ac₄ManNAz to glycoconjugate-bound SiaNAI and SiaNAz, respectively. Six cell lines were cultured in media supplemented with 50 μM Ac₄ManNAI or Ac₄ManNAz. After 72 hours, cells were lysed and the lysates subjected to sialic acid quantification. In every cell line, metabolic labeling with SiaNAI was substantially more efficient than with SiaNAz. For example, in the human prostate cancer cell line LNCaP, 78% of glycoconjugate-bound sialic acids were substituted with SiaNAI.

By contrast, SiaNAz constituted only 51% of LNCaP glycan-associated sialic acids under the same metabolic labeling conditions. Fluorescence microscopy analysis of Ac₄ManNAI-labeled cells after reaction with biotin-azide via CuAAC and staining with FITC-streptavidin confirmed that SiaNAI-modified glycans reside on the cell surface (see Supporting Information).

To determine whether the superior metabolic conversion efficiency of Ac₄ManNAI observed in cell culture is recapitulated *in vivo*, we evaluated its conversion to SiaNAI after administration to laboratory mice. B6D2F1/J mice were injected intraperitoneally with Ac₄ManNAI (300 mg/kg) or vehicle once daily for seven days (Figure 3). On the eighth day, the mice were euthanized, and a panel of organs was harvested and homogenized. The presence of glycoprotein-associated alkynes in the soluble fraction of homogenates was probed by CuAAC with biotin-azide, followed by Western blot analysis. As shown in Figure 4, labeling was observed in organ lysates from mice treated with Ac₄ManNAI but not in organ lysates from vehicle-treated mice. Labeled glycoproteins were observed in lysates from the bone marrow, thymus, intestines, lung, spleen, heart, and liver, but not the kidney. These results indicated that Ac₄ManNAI is metabolized *in vivo* and has access to most organs. Furthermore, during this one-week period, no toxic side effects were observed, suggesting that Ac₄ManNAI is well tolerated by the mice.

We then performed comparative *in vivo* metabolism studies of Ac₄ManNAI and Ac₄ManNAz using a similar protocol. The organs were harvested as described above, and the soluble fractions of the organ lysates were reacted with either biotin-azide or a biotin-alkyne derivative[21] using the same CuAAC conditions. Similar to our observations using cultured cells (Table 1), Ac₄ManNAI treatment produced stronger labeling in organ lysates than Ac₄ManNAz (Figure 5). Based on quantification by densitometry, we estimate that the labeling using ManNAI is at least 25% greater than that using ManNAz (see Supporting Information). However, estimating metabolic incorporation based on these data is difficult because CuAAC displays different reaction kinetics when the limiting reagent is the alkyne compared to the azide.[28] Given that the reaction kinetics are faster by approximately 2–3 fold in the latter case, we believe our estimate based on densitometry to be a lower limit.

In summary, we have demonstrated that Ac₄ManNAI can metabolically label sialic acids in cultured cells and mice with greater efficiency than Ac₄ManNAz. The alkynyl sugar may therefore be useful in the discovery of sialylated cancer biomarkers using murine cancer models. Moreover, these results underscore the sensitivity of sialic acid biosynthetic enzymes to subtle differences in the *N*-acyl structures of the two ManNAc analogs. Accordingly, further structural modulation of alkynyl and azido ManNAc analogs is worth pursuing in order to further increase metabolic labeling efficiency *in vivo*.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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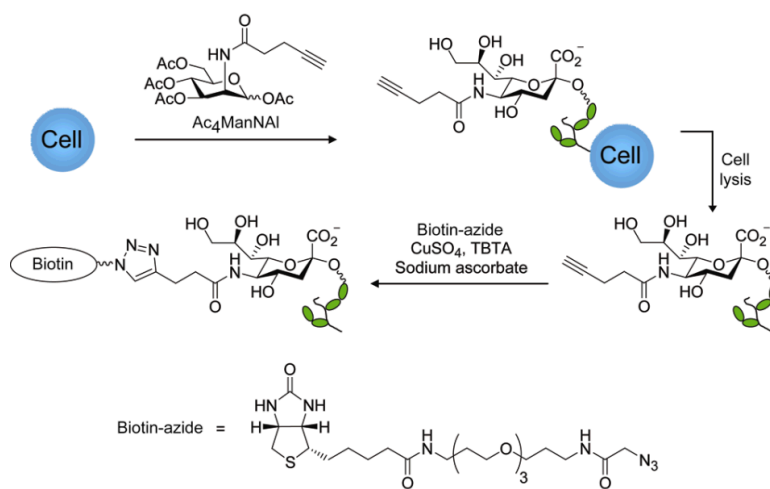


Figure 1. Schematic for metabolic labeling of cellular glycans with Ac₄ManNAI and detection with Cu(I)-catalyzed click chemistry.

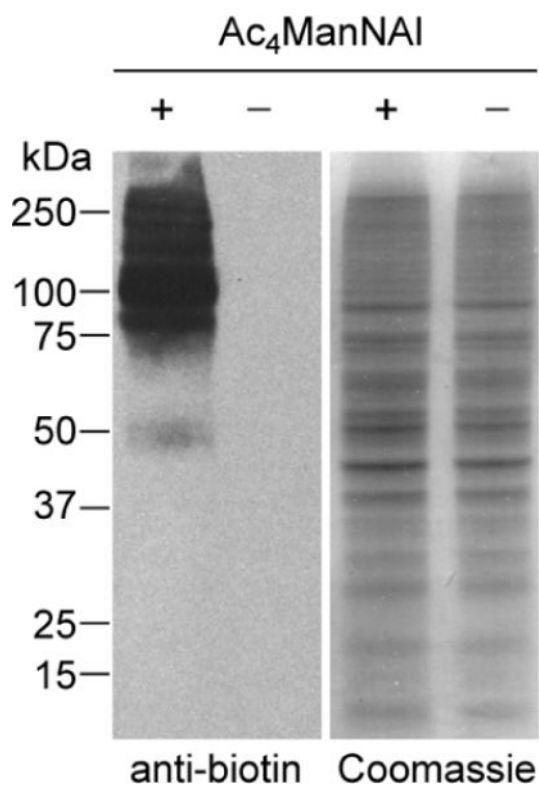


Figure 2. Western blot analysis of lysates from Jurkat cells treated with Ac_4ManNAI (50 μM) or no sugar. The lysates were reacted with biotinazide (100 μM) in the presence CuSO_4 (1 mM), sodium ascorbate (1 mM), and the tris-triazolyl ligand TBTA[14] (100 μM) for 1 h at rt and analyzed by Western blot using an HRP-conjugated anti-biotin antibody (left panel). Total protein loading was confirmed by Coomassie staining of a duplicate protein gel (right panel).

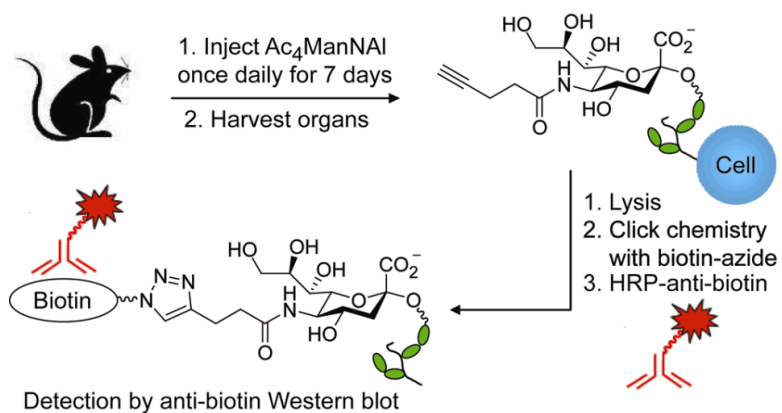


Figure 3. Experimental overview for probing Ac₄ManNAI metabolism *in vivo*. Wild-type B6D2F1/J mice were injected with Ac₄ManNAI or vehicle intraperitoneally once daily for seven days. On the eighth day, the organs were collected and homogenized, and organ lysates were probed using click chemistry for the presence of alkyne-bearing glycoproteins by reaction with biotin-azide, followed by Western blot analysis using an HRP-conjugated anti-biotin antibody.

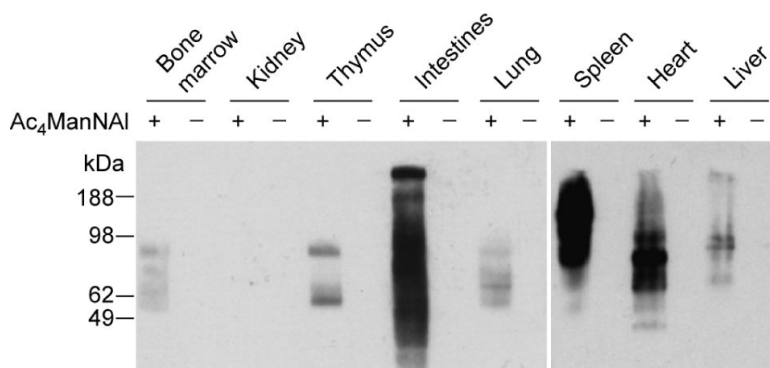


Figure 4.

Western blot analysis of tissue lysates from B6D2F1/J mice administered Ac₄ManNAI (+) or vehicle (-). Mice were injected with Ac₄ManNAI (300 mg/kg) or vehicle once daily for seven days. On the eighth day, the organs were harvested and homogenized. The lysates were then reacted with biotin-azide (100 μM) in the presence CuSO₄ (1 mM), sodium ascorbate (1 mM), and TBTA (100 μM) for 1 h at rt and analyzed by Western blot using an HRP-conjugated anti-biotin antibody. Shown are representative data from three replicate experiments. Total protein loading was confirmed by Coomassie Blue staining of a duplicate protein gel (data not shown).

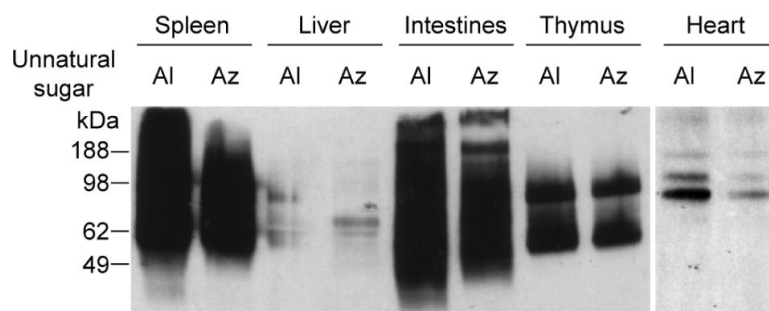


Figure 5. Ac₄ManNAI is converted to the corresponding sialic acid more efficiently than Ac₄ManNAz in mouse organs. A panel of organ lysates from mice treated with Ac₄ManNAI (Al) or Ac₄ManNAz (Az) (300 mg/kg) for 7 d were reacted with 100 μ M biotin-azide or biotin-alkyne[21], respectively, in the presence CuSO₄ (1 mM), sodium ascorbate (1 mM), and TBTA (100 μ M) for 1 h at rt and analyzed by Western blot using an HRP-conjugated anti-biotin antibody. Shown are representative data from three replicate experiments. Total protein loading was confirmed by Coomassie Blue staining of a duplicate protein gel (data not shown).

Table 1

Incorporation percentage of SiaNAI vs. SiaNAz *in vitro*.^[a]

Cell line	Jurkat	HEK 293T	CHO	LNCaP	DUI45	PC3
% SiaNAI	74±1	46±2	38±2	78±1	58±2	71±6
% SiaNAz	29±2	27±2	20±4	51±2	40±3	56±2

[a] The cells were metabolically labeled with 50 μ M Ac4ManNAI (top row) or Ac4ManNAz (bottom row) for 3 d and then lysed. Identification and quantification of SiaNAI and SiaNAz was determined by comparison with synthetic standards according to established procedures.[24] The error represents the standard deviation from the mean of at least three replicate experiments.