The clinical relevance of glycobiology

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The study of protein-bound glycans dates back to the 19th century (1). Until recently these macromolecules have played second fiddle to their cousins, the nucleic acids and proteins. This is not surprising in view of the stunning advances during the second half of the 20th century in the DNA-RNA-protein paradigm, which Francis Crick called the Central Dogma. Since information transfer is a key ingredient of this dogma, it is relevant to point out that the diversity of linkages and branching patterns between monomer building blocks confers on carbohydrates the ability to carry an enormous amount of information in very compact structures (2). These structures therefore carry “more information bang for the buck” than do the other, simpler polymers. The cell surface is covered with protein- and lipid-bound glycans. These structures vary significantly between cell types and at different stages of mammalian development and probably play important roles in the interaction of a cell with its cellular and fluid environment (3–5). Glycoproteins and proteoglycans are essential for normal development in mice (6–16), Drosophila melanogaster (17–20), and Caenorhabditis elegans (18, 21–26). Table 1 lists mice with null mutations in genes required for glycosylation; other null mutant mice are described in reviews by Stanley (9) and Varki and Marth (11).

In spite of all the evidence showing the importance of glycans for metazoan development, glycobiology did not earn the respect it deserves until the recent description of several human congenital diseases with defects in the glycosylation of proteins (27–32). Since at least 0.5–1% of the transcribed human genome is devoted to the production of proteins involved in the synthesis, degradation, and function of glycoconjugates (11), it is likely that we have seen only the tip of the iceberg. Two papers in this issue of the JCI (Schenk et al., ref. 33; and Kranz et al., ref. 34) support this suggestion. These papers describe a congenital disorder of glycosylation (CDG) in which the defective gene encodes an unusual protein with a role in glycan synthesis that is not as clearly defined as were the defects in the previously described human CDGs shown in Table 2.

Table 1

<table>
<thead>
<tr>
<th>Missing enzyme</th>
<th>Biochemical role</th>
<th>Phenotype</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>β1,2-GlcNAc-transferase I</td>
<td>Addition of GlcNAc to the Man3 modified complex N-glycan core</td>
<td>Mice cannot make complex N-glycans.</td>
<td>7, 8</td>
</tr>
<tr>
<td>β1,2-GlcNAc-transferase II</td>
<td>Addition of GlcNAc to the Man6 modified complex N-glycan core</td>
<td>Perinatal lethality; a few survivors (about 1% mimic CDG-IIla (see Table 2)</td>
<td>6</td>
</tr>
<tr>
<td>β1,6-GlcNAc-transferase V</td>
<td>Addition of GlcNAc to the Man6 modified complex N-glycan core</td>
<td>Viable mice. Suppression of tumor growth and metastasis</td>
<td>10</td>
</tr>
<tr>
<td>Dol-P GlcNAc-1-phosphate transferase</td>
<td>Transfers GlcNAc-1-phosphate to Dol-P to make GlcNAc-PP-Dol</td>
<td>Mice cannot make any LLOs.</td>
<td>12</td>
</tr>
<tr>
<td>Ser/Thr O-GlcNAc-transferase</td>
<td>Adds GlcNAc in O-glycosidic linkage to Ser/Thr of many intracellular proteins</td>
<td>Deletion of this X-linked gene causes loss of embryonic stem cell viability</td>
<td>13</td>
</tr>
<tr>
<td>β1,3-Gal-transferase III</td>
<td>Adds Gal to GlcNAc-R, homologue of Drosophila Brainiac</td>
<td>Embryonic lethality prior to implantation</td>
<td>14</td>
</tr>
<tr>
<td>α3,6-mannosidase II</td>
<td>Removes 2 Man residues from GlcNAcMan6GlcNAc2AsnX</td>
<td>Defective synthesis of complex N-glycans Mimics congenital dyserythropoietic anemia type II (HEMPAS) Causes autoimmune disease (see Table 2)</td>
<td>15, 16</td>
</tr>
</tbody>
</table>

HEMPAS, hereditary erythroblastic multinuclearity with a positive acidified serum lysis test.
phosphate oligosaccharides (lipid-linked oligosaccharides; LLOs) in the patient fibroblasts are Man5GlcNAc2 (Figure 1c) and Man9GlcNAc2 (Figure 1b), a novel pattern suggesting defects in both dolichol phosphate mannose-dependent (Dol-P-Man–dependent) mannosylation and dolichol phosphate glucose-dependent (Dol-P-Glc–dependent) glucosylation, respectively. Surprisingly, the two dolichol phosphate monosaccharide precursor synthases and the respective glycosyltransferases are all normal. In fact, whereas all five of the previously described CDG-I types (CDG-Ia to -Ie) are due to defects in enzymes within the synthetic pathways that lead to Glc3Man9GlcNAc2-pyrophosphate-dolichol, the mechanism of action of the protein (Lec35p) responsible for CDG-If has not yet been determined.

Table 2
Human congenital disorders with defective glycosylation

(1) CDG Group I: Defects in N-linked protein glycosylation due to deficiencies in the assembly of the dolichylpyrophosphate-linked oligosaccharide and/or its transfer to asparagine residues on the nascent polypeptides.

<table>
<thead>
<tr>
<th>CDG type</th>
<th>Enzyme defects</th>
<th>Gene</th>
<th>OMIM^</th>
<th>Locus Link^</th>
<th>Acronym</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ia</td>
<td>Phosphomannomutase 2</td>
<td>PMM2</td>
<td>212065</td>
<td>5373</td>
<td>CDG-Ia</td>
</tr>
<tr>
<td>Ib</td>
<td>Phosphomannose isomerase</td>
<td>MPI</td>
<td>602579</td>
<td>4351</td>
<td>CDG-Ib</td>
</tr>
<tr>
<td>Ic</td>
<td>Dolichyl-P-Glc:Man5GlcNAc2-PP-dolichyl α1,3-Glucosyltransferase</td>
<td>ALG6</td>
<td>603147</td>
<td>29929</td>
<td>CDG-Ic</td>
</tr>
<tr>
<td>Id</td>
<td>Dolichyl-P-Man:Man5GlcNAc2-PP-dolichyl α1,3-Mannosyltransferase</td>
<td>NOT56L</td>
<td>601110</td>
<td>10159</td>
<td>CDG-Id</td>
</tr>
<tr>
<td>Ie</td>
<td>Dolichol-P-Man synthase 1</td>
<td>DPM1</td>
<td>603503</td>
<td>8813</td>
<td>CDG-Ie</td>
</tr>
<tr>
<td>If</td>
<td>Dolichol-P-Man utilization defect 1; Lec35</td>
<td>MPDU1</td>
<td>604041</td>
<td>9526</td>
<td>CDG-If</td>
</tr>
<tr>
<td>Ix</td>
<td>Genetic basis unknown</td>
<td></td>
<td>603585</td>
<td>212067</td>
<td>CDG-Ix</td>
</tr>
</tbody>
</table>

(2) CDG group II: Defects in the processing of N-glycans or addition of other glycans to proteins.

<table>
<thead>
<tr>
<th>CDG type</th>
<th>Enzyme defect</th>
<th>Gene</th>
<th>OMIM^</th>
<th>Locus Link^</th>
<th>Acronym</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iia</td>
<td>UDP-GlcNAc:x6-D-mannoside β1,2- N-acetylgalcosaminyltransferase II (GnT II)</td>
<td>MGAT2</td>
<td>212066</td>
<td>4247</td>
<td>CDG-Iia</td>
</tr>
<tr>
<td>Iib</td>
<td>α1,2-Glucosidase I</td>
<td>GCST</td>
<td>601336</td>
<td>7841</td>
<td>CDG-Iib</td>
</tr>
<tr>
<td>Iic</td>
<td>GDP-fucose transporter I</td>
<td>FUCT1</td>
<td>266265</td>
<td>55343</td>
<td>CDG-Iic</td>
</tr>
</tbody>
</table>

(3) Other.

<table>
<thead>
<tr>
<th>Name of disease</th>
<th>Enzyme defect</th>
<th>Gene</th>
<th>OMIM^</th>
<th>Locus Link^</th>
<th>Acronym</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEMPAS</td>
<td>α3,6-Mannosidase II; other unknown defects</td>
<td>MAN2A</td>
<td>224100</td>
<td>4124</td>
<td>CDA II</td>
</tr>
</tbody>
</table>

^OMIM, Online Mendelian Inheritance in Man; Locus Link summarizes all the known information on a particular gene. Both databases can be accessed at http://www.ncbi.nlm.nih.gov/. LAD II, leukocyte adhesion deficiency type II. CDA II, congenital dyserythropoietic anemia type II.

The name Lec35 derives from a lectin-resistant Chinese hamster ovary (CHO) mutant cell line that accumulates Man5GlcNAc2-pyrophosphate-dolichol (Figure 1c) (36). The Lec35 protein was shown to be required for the utilization of both Dol-P-Man and Dol-P-Glc and, consequently, for the mannosylation and glucosylation of LLOs, the mannosylation of glycosylphosphatidylinositols, the C-man-

![Figure 1](image-url)

(a) The structure of Glc3Man9GlcNAc2-pyrophosphate-dolichol. This compound is essentially the only LLO found in normal human fibroblasts. However, appreciable amounts of this material are also found in all CDG-I fibroblasts reflecting the "leaky" nature of the mutations in these patients. Based on animal studies, total lack of this LLO is not compatible with life. (b) The structure of Man9GlcNAc2-pyrophosphate-dolichol. This is one of the major LLOs found in CDG-If. The accumulation of this compound implies a defect in the addition of Glc in α1,3 linkage to the Man at the arrow. Since the synthesis of Dol-P-Glc and the activity of the relevant Dol-P-Glc–dependent α1,3-glucosyltransferase are both normal in CDG-If, the defect has been attributed to an inability to utilize Dol-P-Glc. (c) The structure of Man5GlcNAc2-pyrophosphate-dolichol. This is the other major LLO found in CDG-If. The accumulation of this compound implies a defect in the addition of four Man residues to the Man at the arrow by four Dol-P-Man–dependent mannosyltransferases. Since the synthesis of Dol-P-Man and the activities of the relevant mannosyltransferases are normal in CDG-If, the defect has been attributed to an inability to utilize Dol-P-Man.
nosylation of tryptophanyl residues, and protein O-mannosylation (37). These results show that Lec35p has an essential role for all known classes of dolichol phosphate monosaccharide-dependent glycosyltransferase reactions in mammals. The human Lec35 ortholog has been named MPDU1 (mannose phosphate dolichol utilization defect 1) and was mapped to 17p12-13. Sequence analysis of the MPDU1 gene showed distinct mutations in all four CDG-II patients. The predicted amino acid sequence of Lec35p does not suggest an obvious function or mechanism. Lec35p is a 27-kDa endoplasmic reticulum membrane-associated protein with two putative transmembrane segments and is probably involved in the “flipping” of Dol-P-Man and Dol-P-Glc from the cytoplasm, where these molecules are synthesized, to the lumen of the endoplasmic reticulum, where glycosylation occurs. The use of mutant mammalian cell lines (such as lectin-resistant CHO lines) and yeast mutants has been essential for the elucidation of many CDG types, including CDG-II.

Phenotypic variability among the CDG individuals

The complexity of the various glycosylation pathways suggests that many congenital diseases of unknown etiology will turn out to be CDGs. One major reason is the diversity of clinical presentation and severity in the CDG spectrum. This is true even in a single type of CDG (for example, the four cases of CDG-II described in this issue of the JCI) [refs. 33, 34]. The same diversity occurs in the broader spectrum of CDG-I even though all known types are due to defective synthesis of GlcManGlcNAc2-pyrophosphate-dolichol. For example, the enzymes responsible for CDG-Ia (phosphomannomutase 2) and CDG- Ib (phosphomannose isomerase) sit side by side in the synthetic pathway leading to Dol-P-Man, yet the clinical presentations of the two diseases differ enormously: CDG-Ia patients show severe psychomotor retardation, whereas CDG-Ib patients have no neurological defects. The biochemical findings within a single CDG type also tend to vary; for example, the lipid- and protein-bound oligosaccharide patterns can differ quite dramatically between patients. This is perhaps not surprising in view of the various deglycosylation and reglycosylation pathways involved (38–40). There are almost certainly other as-yet-unknown factors — genetic, regulatory, environmental, etc. — that contribute to differences between CDG patients (28). Both under- and overglycosylation may cause disease, and it may be necessary to strike a healthy balance between the two (28). The relative frequency of certain CDG mutant alleles suggests that they may have advantages in the heterozygous state, e.g., protection against viral infection (28).

The search for new CDG types can benefit from animal models, which may show phenotypic changes that differ from the human clinical presentations. Indeed, comparison of Tables 1 and 2 shows that only two known mouse glycosylation defects correspond to identified human CDGs, namely CDG-Ila and the atypical CDG HEMPAS (hereditary erythroblast multinuclearity with a positive giedtified serum lysis test). Hence, there are almost certainly more CDGs to be described, and clinicians should think of CDG whenever they are faced with a puzzling congenital disease. Of the human diseases, only CDG-Ib and -IIc have, to date, responded to therapy — oral mannose and fucosé, respectively. Further research may improve this picture as it reveals more fascinating facts about glyobiology.

26. Berninsons, P., Hwang, H.Y., Zemseva, 1,


