**Brief Review**

**ABO Blood Group as a Model for Platelet Glycan Modification in Arterial Thrombosis**

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**Abstract**—ABO blood groups have long been associated with cardiovascular disease, thrombosis, and acute coronary syndromes. Many studies over the years have shown type O blood group to be associated with lower risk of cardiovascular disease than non–type O blood groups. However, the mechanisms underlying this association remain unclear. Although ABO blood group is associated with variations in concentrations of circulating von Willebrand Factor and other endothelial cell adhesion molecules, ABO antigens are also present on several platelet surface glycoproteins and glycosphingolipids. As we highlight in this platelet-centric review, these glycomic modifications may affect platelet function in arterial thrombosis. More broadly, improving our understanding of the role of platelet glycan modifications in acute coronary syndromes may inform future diagnostics and therapeutics for cardiovascular diseases. (Arterioscler Thromb Vasc Biol. 2015;35:00-00. DOI: 10.1161/ATVBAHA.115.305337.)

**Key Words:** ABO blood-group systems ■ acute coronary syndrome ■ blood platelets ■ glycoproteins ■ thrombosis

Cardiovascular disease (CVD), including coronary artery disease (CAD), cerebrovascular disease, and peripheral vascular disease, is a leading cause of morbidity and mortality throughout the world and the United States. According to the American Heart Association, CVD accounted for 31.9% of all mortality within the United States in 2010, with 1 of every 6 deaths attributable to CAD.1 Despite some success in reducing rates of heart disease, these realities demand new innovations to CAD prevention and novel therapeutic strategies.

Vascular inflammation, driven by hyperlipidemia and diverse risk factors, promotes leukocyte recruitment and transmigration to the subendothelium, mediated in large part by adhesion molecules, chemokines, and cytokines expressed on endothelial cells and leukocytes.2 Once atherosclerotic lesions have developed, physical and inflammatory disruption of these plaques incites a platelet-dependent thrombosis and acute coronary syndrome (ACS).

An active area of research is the role of the ABO blood group locus and glycosyltransferases in the pathophysiology of CAD and ACS. A multitude of studies has shown an association between non-O blood groups and both prevalence and incidence of CAD,3,4 as well as increased mortality in patients with ischemic heart disease;5 and size of myocardial infarction (MI) during ACS.6 The mechanism behind the association of ABO blood type and CVD has been studied but not yet clearly elucidated. One potential mechanism is that ABO glycosyltransferases modify platelet surface glycoproteins and glycolipids, resulting in terminal modifications that impact the function of platelets. Understanding the ways in which ABO glycans modulate platelet glycoprotein and glycolipid function with respect to platelet activation, aggregation and platelet-driven thrombosis may improve our knowledge of the mechanisms underlying arterial thrombosis and ACS. Thus, this review will examine the existing knowledge of ABO blood group effects on CAD and ACS with a specific focus on the potential impact of ABO on platelet function and arterial thrombosis, while also considering more broadly the impact of diverse glycomic modifications on platelet function and biology.

**ABO Blood Group, Thrombosis, and ACSs**

ABO blood group phenotype is determined by the expression of specific antigens on red blood cells, endothelial cells, platelets, and many other cells and tissues. The presence of A or B antigen results in the expression of A, B, or AB phenotype, whereas the lack of both A and B antigen results in the expression of the O phenotype. These ABH antigens comprise complex terminal carbohydrate molecules on glycoproteins and glycolipids, generated by the addition of N-acetylgalactosamine (A antigen) or α-galactose (B antigen) to existing N-glycan and O-glycan structures through the action of the ABO glycosyltransferases.7 The A and B alleles of the ABO locus encode A and B glycosyltransferases, which in turn catalyze the transfer of the different carbohydrates onto a common core H antigen, to form an A or B antigen.8 Further, the action of the ABO glycosyltransferases can also add H antigen to the N-glycan of glycoproteins, generating the H antigen on glycoproteins.9 Thus, the ABO blood group system influences the expression of glycoproteins on the cell surface, affecting cell adhesion and recognition.10,11

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B antigen. However, type O individuals only express H antigen because the O isoform of ABO lacks glycosyltransferase activity.\(^8\)

In the past, studies have associated ABO blood groups with CVD, whereby non–type O blood groups are associated with higher risk of CVD, MI, and thrombosis than type O blood group.\(^9\) Previous genome-wide association studies (GWAS) have also identified associations between ABO blood type and cardiovascular risk factors, such as serum cholesterol and low-density lipoprotein,\(^9\) implying a role of blood type and cardiovascular risk factors.

GWAS have also identified associations between ABO genotype and cardiovascular risk factors, such as serum cholesterol and low-density lipoprotein,\(^9\) implying a role of ABO blood group individuals in the presence of existing coronary artery disease.\(^10\) The same ACS/MI ABO locus variants also associate with circulating von Willebrand factor (VWF), whereas non–type O blood group O carriers.\(^15\) The Cohorts for Heart and Aging Research in Genome Epidemiology Consortium GWAS did not find any ABO polymorphisms associated with factor VIII levels independent of blood levels of VWF.\(^19\) These results imply that ABO’s association with serum factor VIII levels are likely attributable to VWF complexing with factor VIII in circulation.

Although ABO blood type is associated with circulating levels of VWF (single nucleotide polymorphisms that tag the ABO blood groups account for 15.4% of the log variance), there are several other mechanisms that regulate VWF concentration. Studies of healthy European cohorts have shown that VWF level varies depending on age, body mass, and common polymorphisms within the VWF gene.\(^20\) In addition, murine models have been developed with expression of both increased and decreased levels of VWF,\(^21\) despite the fact that mice do not express ABH antigenicity. At least part of this variance in VWF level is thought to be caused by differences in the level of VWF sialylation. This hypothesis was investigated by McGrath et al,\(^13\)\(^,\)23 where desialylated VWF was more prone to cleavage by serine and cysteine proteases, but less susceptible to cleavage by ADAMTS supporting the idea that similarly to ABO glycosylation, sialylation of VWF may alter its rate of clearance. In fact, the effect of sialylation may even be understated, as erythrocytes and platelets lose their sialic acid during blood banking via irreversible membrane alterations.\(^24\) Although it is unknown whether VWF loses sialic acid during sampling, any tendency for ex vivo desialylation could make it more difficult to identify the specific targets of sialylation that ultimately impact VWF level.

Beyond associations with levels of circulating VWF, blood group phenotype is also thought to affect endothelial–leukocyte interactions and leukocyte recruitment and transmigration to inflamed endothelium by influencing serum levels of endothelial-derived adhesion molecules, including soluble P-selectin, E-selectin, and intercellular adhesion molecule-1. A large-scale GWAS by Barbalic et al\(^25\) suggested that both soluble P-selectin and soluble intercellular adhesion molecule-1 are associated with ABO polymorphisms, with lower levels of sP-selectin and soluble intercellular adhesion molecule-1 associated with A1 and A2 blood group alleles. Similarly, a GWAS by Paterson et al\(^26\) demonstrated that polymorphisms around the ABO locus are associated with soluble E-selectin levels, accounting for ≤19% of variability, with highest concentrations associated with type O blood group. Notably, the direction of ABO blood group association with blood levels of these endothelial-derived adhesion molecules is opposite to that for VWF. Yet, it remains unclear how blood adhesion molecule associations occur, ie, via glycan modifications that alter secretion,
cleavage, turnover, or clearance. Despite the association between blood group O and lower rates of cardiovascular events, blood group O carriers have higher levels of soluble P-selectin and soluble intercellular adhesion molecule-1. Yet higher concentrations of these adhesion molecules are actually associated with increased risk for cardiovascular events.\(^2\) One potential explanation for this confusing observation is that ABO phenotype affects the concentration of adhesion molecules differently during acute pathophysiologies, such as ACS/MI compared with at rest. It is also possible that the function of adhesions molecules, in addition to the concentration, differs among ABO groups. Although these associations have been studied with soluble cell adhesion molecules, ABO glycan may also have an impact on levels or function of intracellular or membrane-bound adhesion molecules on endothelial cells, which play a direct role in leukocyte–platelet–endothelial interactions.

ABO blood group associations may promote ACS/MI in additional ways beyond the effect on serum concentrations of VWF and cell adhesion molecules via distinct modulation of plaque rupture, platelet-dependent thrombosis, or both. Although platelet counts do not differ by blood group,\(^3\)–\(^6\) ABH antigens are expressed on both platelet membrane lipids and platelet glycoproteins, and these may influence platelet interactions with fibrinogen and VWF, thereby modulating platelet aggregation and platelet-driven thrombosis.

**ABO Expression on Platelet Glycoproteins and Glycolipids**

**Platelet Glycoproteins**

Blood type A and B carbohydrate antigens are expressed on platelet glycoproteins, including several glycoproteins that play key roles in thrombotic pathways. Santos et al\(^2\) discovered the presence of ABH antigenicity on platelet glycoproteins IIa and IIIa, as well as the glycoprotein IIb/IIIa complex by utilizing anti-A and anti-B IgG antibodies and radioimmunoprecipitation. The glycoprotein IIb/IIIa receptor complex mediates platelet aggregation in ACS and MI via binding of fibrinogen, fibronectin, and VWF.\(^2\) The role of glycoprotein IIb/IIIa in arterial thrombosis has been highlighted by numerous studies showing the benefits of targeting the glycoprotein complex.\(^2\) Similarly, glycoprotein IIa is a part of the glycoprotein Ia/IIa complex, which binds collagen and stabilizes platelets to exposed collagen at sites of injured endothelium. It is possible that ABO modification of this glycoprotein complex may also impact its function and expression, thereby affecting platelet function in arterial thrombosis. Therefore, knowledge of the extent and exact locations of ABO modification of glycoproteins Ia/IIa and IIb/IIIa may provide additional insight into the mechanistic underpinnings of platelet aggregation and thrombosis in ACS and MI and also impact future drug therapies. ABH antigens are expressed on several other platelet glycoproteins, including glycoprotein Ib,\(^7\) glycoprotein IV, and glycoprotein V.\(^3\) Glycoproteins Ib and V are a part of the glycoprotein Ib–IX–V complex, which mediates platelet adhesion to injured endothelium via the binding of VWF and thereby initiates events leading to thrombosis.\(^2\) Platelet glycoprotein Ib–IX–V complex is proposed to play a significant role in arterial thrombosis during shear-induced binding of VWF in the setting of abnormal blood flow and shear at sites of atherosclerosis. This binding subsequently induces platelet activation and aggregation via the binding of thrombin and VWF to initiate the formation of a thrombus.\(^3\) ABH antigenicity is also expressed on platelet endothelial cell adhesion molecule-1 (PECAM-1).\(^2\) PECAM-1 is a glycoprotein expressed on the surface of platelets and endothelial cells and is thought to play a role in atherogenesis via leukocyte adhesion and transmigration.\(^2\) Yet, recent studies by Falati et al\(^2\) used PECAM-1–deficient mice to show that arteriolar thrombi, induced by laser injury, were larger and formed more rapidly. Thus, PECAM-1 seems to be a negative regulator of platelet-driven thrombosis in vivo. ABO glycomic modifications of PECAM-1 may have a functional impact on platelet-driven thrombosis. Understanding the impact of these platelet-related glycan and glycoprotein modifications may inform future diagnostics and therapeutics, specifically targeting ABO-modified platelet glycoproteins.

One novel mechanism by which glycan modifications of platelet glycoproteins may alter platelet function is via galectin–glycan interactions. Galectins are a family of proteins, which specifically bind \(\beta\) galactosides, glycans, which can be bound to proteins via N-linked or O-linked glycosylation.\(^3\) Galectins are expressed both extracellularly, in circulation and within extracellular matrices, and intracellularly within the nucleus, cytoplasm, and outer plasma membrane. Furthermore, galectins are expressed within a variety of tissue, including endothelial, epithelial, and adipose tissue. There have been 15 unique galectins discovered although only 12 are present in humans, where different galectins can recognize different glycan structures and with different affinities. Galectins Gal-1 and Gal-8 can act as potent platelet agonists, inducing both platelet aggregation via a conformational change of glycoprotein IIb/IIIa\(^3\) and platelet adhesion to an extracellular matrix. These galectins are able to mediate their effects on platelets by interacting with specific platelet surface glycans expressed on glycoproteins. Gal-8 binds platelet surface glycoprotein Ib and glycoprotein IIB, whereas the exact targets for Gal-1 are still unknown.\(^3\) It is possible that ABO glycan modifications could affect how platelet glycoproteins interact with their respective galectins, thereby affecting platelet activation, adhesion, and aggregation.

**Platelet Glycolipids**

Platelet glycosphingolipids also play a prominent role in platelet activation, aggregation, and thrombosis\(^4\)–\(^7\) by modulating transmembrane signal transduction. These glycosphingolipids affect platelet function by interacting with various cell adhesion molecules such as P-selectin, fibrinogen, and VWF. In a study by Merten, sulfatide, a sulfated glycosphingolipid, was found to affect platelet adhesion by acting as a ligand to P-selectin, where exposure to a sulfatide antagonist decreased the extent of platelet adhesion.\(^2\) Guchhait et al\(^2\) further illustrated the role of sulfatide, by exposing platelets to a sulfatide antibody probe. By blocking sulfatide, they inhibited platelet...
functions in platelets, however, remain uncertain particularly
platelets.47 The role and impact of ABO on glycosphingolipid
expressing B antigenicity have been identified on type B
ABH antigenicity on RBCs. Similarly, glycosphingolipids
the complex, branched glycosphingolipids that express
type A platelets. Although the exact structures of the 5 acidic
glycosphingolipids were identified that also express A antigenicity
on type A platelets.48

Beyond sulfated glycosphingolipids, platelet surfaces
express many neutral glycosphingolipids and silylated
glycosphingolipids, known as gangliosides, with the most
abundant being hematoside (GM3), globoside, and trihexo-
sylceramide.44 These platelet surface glycosphingolipids
and gangliosides undergo both quantitative and qualitative
changes during platelet activation, thereby affecting plate-
et adhesion and aggregation. Wang and Schick44 demonstr-
ated that exposure of platelets to thrombin reduces by
≈50% the surface labeling of trihexosylceramide and glo-
obside, whereas increasing hematoside surface labeling.
Resting platelets predominantly express the ganglioside
GM3 yet platelet activation by ADP, collagen, or arachi-
donide acid increased surface expression of GD3, suggest-
ing that GD3 serves as a messenger in platelet adhesion
and activation.40 Activation of platelets by thrombin recep-
tor agonist peptide increases expression of sulfated gly-
cosphingolipids on the platelet surface. Furthermore, the
addition of micelles containing sulfated glycosphingoli-
oids inhibited platelet adhesion to P-selectin.41 In contrast,
agonists of sulfated glycosphingolipids reduced ADP
and thrombin receptor agonist peptide induced platelet
aggregation, whereas addition of sulfated glycosphingoli-
oids increased the extent of platelet aggregation in ex vivo
activated platelets.41,42 Similarly, Santoro45 demonstrated
the inhibitory effect of exogenously added gangliosides on
platelet adhesion to fibronectin, fibrinogen, and VWF and
discovered that the inhibitory effect varied with the number
of sialic acid residues expressed by the added gangliosides.
These results suggest that platelet function may be modu-
lated by gangliosides and their post-translational modifi-
cations. Although further mechanistic and clinical studies
are required, overall these data support the concept of a
functional role for the dynamic and regulated expression of
specific glycosphingolipids during platelet activation and
in arterial thrombosis.

Like platelet glycoproteins, ABH antigenicity is also
expressed on platelet surface glycosphingolipids. Cooling et
al46 demonstrated that neutral glycosphingolipids, hexosyl-
ceramide (A6), and octaosylceramide (A8) express A anti-
genicity in type A platelets, whereas no ABH antigenicity
was identified on type O platelets. Similarly, 5 acidic glycosphin-
golipids were identified that also express A antigenicity on
type A platelets. Although the exact structures of the 5 acidic
glycosphingolipids could not be identified, it is thought that
they are likely monosialo, long-chain gangliosides, unlike
the complex, branched glycosphingolipids that express
ABH antigenicity on RBCs. Similarly, glycosphingolipids
expressing B antigenicity have been identified on type B
platelets.47 The role and impact of ABO on glycosphingolipid
functions in platelets, however, remain uncertain particularly
because published work suggests that only a small propor-
tion (estimated at <1%) of all known platelet glycosphingo-
lipids and gangliosides may carry ABH antigens.46 Although
limited in quantity, these post-translational modifications of
glycosphingolipids may have important effects on platelet
function.

Variability in ABO Expression on Platelets
The degree of ABH antigenic expression on platelet glyco-
proteins and glycolipids varies not only across ABO blood
groups but also within individuals of the same blood group.
Hou et al44 demonstrated that blood group A and B antigens
are heavily associated with glycoprotein Ib and glycoprotein
IIb, with glycoprotein IIb being the most prominent. However,
there were differences in antigenic expression, even within
a specific blood group phenotype. For example, blood group A
is characterized by 2 specific subgroups, A1 and A2, where
the A2 genotype represents a mutation involving single base
deletion, which ultimately results in an A2 glycosyltransferase
with 30- to 50-fold less activity than A1.48 In examining these
subgroups, platelets with the A2 polymorphism do not express
A antigens on glycoproteins Ib and IIb and expressed only one
tenth the amount of antigen on glycolipids as individual with
A1 platelets.44

Several studies have found that a subset of A and B indi-
viduals express significantly more A and B antigens on their
platelet surfaces than the general population and are termed
high expressers. Roughly 7% of type A individuals and 4%
to 7% of type B individuals are high expressers for A and B
antigen expression, with higher levels of A and B anti-
gens expressed on glycoprotein Ib/IX, Ia/IIa, IV, PECAM,
IIb/IIIa. While examining type A individuals, Curtis et al34
used flow cytometry to discover that individuals with an A2
polymorphism have undetectable or barely detectable levels
of A antigen, whereas individuals with an A1 polymorphism
express low levels of A antigen. Yet, ≈7% of A1 individuals
and 4% of B individuals expressed A and B antigens
levels >2 SDs above the mean, with higher levels of antigens
on various platelet glycoproteins, but especially glycopro-
tein Ib and PECAM. The mechanism behind this differen-
tial expression may lie in differences in enzymatic activity,
as well as in H antigen abundance and modification; high
expressers concomitantly show higher levels of A1 and B
glycosyltransferase activity and lower levels of H antigen
on their red blood cells.

Subsequent studies further examined the determinants of
differential expression of ABH antigenicity within blood
groups. Cooling et al57 studied 131 type A platelet donors,
where similar to previous studies, A antigen was expressed
on platelet membranes, glycoproteins, and glycosphingo-
lipids of A1 platelets. ABH antigen expression varied sig-
ificantly between donors, but did not vary significantly over
time within donors. Expression was influenced by specific
A subtype, age, and sex, with the A1 versus A2 subtypes
being the greatest predictor of platelet ABH antigen expres-
sion. Concordance was shown between A1 phenotype and
A antigen expression on platelet membranes, glycoproteins,
and glycosphingolipids. Among the A1 phenotype, there was
a linear coexpression of A and H antigens, suggesting that platelet ABH antigen expression is also dependent on the abundance of H antigens, and not solely on A and B glycosyltransferase activity. Similarly, blood group B platelets also displayed differences in the expression of B surface antigen. Ogasawara et al demonstrated that 7% of type B individuals were high expressers for B antigen, with increased levels of B glycosyltransferase activity. In these high expressers, glycoprotein IIb and IIa were shown to express the largest amount of B antigen on the platelet surface. Clinically, high expressers were found to have rapid clearance of ABO mismatched platelet transfusions.

While interesting, the molecular basis and clinical significance of high ABH expression, beyond implications in transfusion medicine, are still being investigated. However, there is already evidence that the level of platelet ABH expression can vary depending on platelet activation and storage conditions, either through granule translocation or changes in glycosyltransferase activity. Therefore, I hypothesis might be that high expression of A or B antigenicity, relative to that of blood group O, influences the risk of coronary thrombosis via the degree of modification of important glycoproteins, such as glycoprotein Ib, glycoprotein IIa, glycoprotein IIb, and PECAM. In addition, the degree and impact of post-translational modification of these platelet glycoproteins may be different at rest and during platelet activation preceding a thrombotic event. Investigating the potential impact of high ABH expression on platelet function at rest and during activation, as well as on other cells involved in arterial thrombosis, such as endothelial cells, may inform diagnostics, through biomarker development and risk prediction and by identifying individuals with atherosclerosis who may be at higher risk for thrombosis and therefore, ACS/MI.

Potential for ABO Modulation of Platelet Function and Arterial Thrombosis

Platelets play a pivotal role in ACS with formation of a platelet aggregate at the site of a ruptured atherosclerotic plaque or locus of endothelial denudation. Platelets adhere to sites of injured vessels via the binding of subendothelial collagen to glycoprotein Ia/IIa and ultimately forming a platelet-rich plug via the binding of VWF or fibrinogen to activated platelet glycoprotein IIb/IIIa, the transmembrane receptor complex that serves as the dominant final common pathway in platelet-driven arterial thrombosis. The importance of platelets in ACS and MI has been established over decades through basic and clinical research, most notably by documentation of acute in vivo platelet activation during ACS and MI and clinical trials that demonstrate the efficacy of oral and parenteral antiplatelet agents in prevention of heart disease and in the treatment of ACS and MI. Thus, ABO modulation of platelet glycolipids, glycoproteins, or circulating proteins that interact with platelets (eg, VWF, which is itself ABO modified) may alter the rate and clinical impact of platelet-driven thrombosis.

Several studies have investigated differences in platelet function and hemostasis markers across blood groups. Moeller et al examined 162 healthy donors with normal in vivo bleeding time end points, factor VIII activity, VWF structure, and ristocetin-induced platelet aggregation. In this study, type O individuals demonstrated a longer bleeding time than non-type O individuals (89±14.6 versus 82±13 s; P<0.01), indicating an in vitro effect of ABO blood group on primary hemostasis. Favaloro et al examined 452 donors across blood groups and demonstrated an association between type O group and lower levels of plasma VWF, collagen binding activity and factor VIII coagulant activity. Interestingly, type O individuals also had lower levels of ristocetin cofactor activities, suggesting a higher rate of platelet aggregation to ristocetin in non-type O individuals. However, there was no association between blood group status and the ratio of total VWF:functional VWF. The authors concluded that ABO blood group may influence platelet adhesion via the binding of VWF, conferring increased rates of thrombosis to blood in non–blood group O carriers.

Feuring et al demonstrated that although ABO blood group was associated with differences in measures of ex vivo platelet function, ABO blood group status did not influence the effect of a range of glycoprotein IIb/IIIa receptor antagonists in blocking the receptor and inhibiting platelet function. These studies suggest that ABO affects certain surrogate in vitro measures of platelet function, possibly via glycan modifications of platelet glycoproteins or glycolipids. However, it remains uncertain what effect, if any, ABO blood group modifications have on clinically relevant platelet function and arterial thrombosis in vivo.

Platelet Glycobiology Beyond ABO Modifications

Despite limitations of present knowledge on the extent, specific targets, and function of ABO modification of platelet glycoproteins and glycolipids, ABO glycosylation may prove to be an important model for the role of glycemic pathways in platelet function and ultimately arterial thrombosis. Studies by Wandall et al have shown that platelets contain functional intracellular and surface glycosyltransferases, with the ability to glycosylate exogenously added glycoprotein Ib, IIb, and VWF. Furthermore, although platelets expressed functional glycosyltransferases at rest, they release ≈50% of their glycosyltransferase activity, as well as sugar nucleotides substrates, on activation by thrombin receptor agonist peptide or ADP. These results suggest that platelets contain a complete glycosylation apparatus, which on activation allows platelets to modify surface glycans. In fact, when human platelets were activated in the presence of mouse platelets, sialic acid was noted to be added to mouse platelet surface glycoprotein Ib. To test the effect of modification of surface glycoproteins on platelet function, the bleeding times of silylated platelets were compared against nonsilylated platelets in vitro. Platelets that incorporated sialic acid into their surface glycoproteins were found to be less responsive, with significantly longer bleeding times than controls.

Post-translational modification of platelet surface glycoproteins can play an important role in determining
platelet-specific alloantigenicity. Bak is a platelet-specific alloantigen expressed on glycoprotein IIb. Take et al.64 tested the hypothesis that post-translational sialylation of glycoprotein IIb affected the expression of Bak epitopes. The authors demonstrated that the binding of 4 anti-Bak sera to Bak changed depending on whether neuraminidase was administered to desilylate glycoprotein IIb. A subsequent study by Goldberger et al.65 demonstrated changes in electrophoretic mobility and reactivity to antisera when Bak<sup>a</sup> and Bak<sup>b</sup> platelets were exposed to neuraminidase, thereby desialylating glycoprotein IIb. The authors concluded that in addition to a change in amino acid 843 of glycoprotein IIb, from isoleucine to serine, post-translational sialylation of glycoprotein IIb was also necessary for the expression of Bak<sup>a</sup> and Bak<sup>b</sup> epitopes.

From a clinical perspective, Davoren et al.66 examined 1162 cases of neonatal alloimmune thrombocytopenia, a disease thought to be mediated by the placental passage of platelet-specific alloantibodies and discovered that alloantibodies to Bak epitopes contributed to 2% of all cases. Other polymorphisms in platelet-specific antigens have also been associated with various disease states, including coronary thrombosis. A study by Weiss et al.67 showed a higher prevalence of PI A2 (39.4 versus 19.1%), a polymorphism on another platelet-specific antigen, in patients with a history of MI or unstable angina compared with controls. Therefore, it is possible that post-translational modification, including sialylation, of platelet glycoproteins can impact platelet function via the differential expression of platelet-specific alloantigens.

Although glycan modification of platelet receptors seems to play a role in platelet function, understanding the exact role of glycan modification of these glycoproteins, including ABO glycans, in resting and during activation of platelets may offer new insights into the pathophysiology of thrombosis and provide opportunities for diagnostic and prognostic translations and for novel therapeutics.

**Systematic Glycomic Profiling of Platelets**

Over the years, many studies have shown that ABO groups are associated with ACS and thrombosis, and that ABH antigens are expressed on platelet surface glycoproteins and glycolipids. However, the specific glycans, glycopeptides, and glycolipids on platelets, modified by ABO glycans, and the manner in which these molecules influence platelet function is still largely unknown. Importantly, work by Wang et al.68 have shown that specific glycan modifications do indeed play an important role in platelet function. Using mice with targeted deletion of Cosmc, an essential chaperone in O-glycosylation regulation, the authors showed increased incidence of hemorrhage and longer bleeding times, as well as decreased glycoprotein Ib–IX–V and glycoprotein IIb/IIIa function in mice with deletion of Cosmc. These findings imply that disruption of O-glycosylation leads to impaired platelet adhesion and clotting via changes in platelet glycoprotein function.

Mass spectrometry and glycan binding lectins can provide additional insights into platelet-specific glycomic modifications by providing information on changes in structure, content, and configuration of specific platelet glycoproteins and glycolipids.69 A recent study by Mercado et al.70 used mass spectrometry to probe the mechanism in which elevated plasma levels of serotonin accelerate platelet aggregation. This study revealed modification of the content of N-glycans on mouse platelet surfaces after infusion of serotonin, with a switch in the N-glycan structures on platelet glycoproteins from predominantly N-acetyl-neuraminic acid to N-glycolyl-neuraminic acid. The authors postulated that these glycoprotein modifications underlie the mechanism by which serotonin enhances platelet aggregation.

To further explore the role of ABO groups in modifying platelet function, the complete extent of N-, O-, and glycosphingolipid species and targets in platelets at rest and during activation will need to be defined in an unbiased manner. Although mass spectrometry has been used to highlight specific proteins in the platelet sheddome71 and within platelet microparticles,72 fractions that contain key local and systemic signals modulating thrombosis in clinical disease, a complete analysis of all glycoprotein and glycosphingolipid species is lacking. In the context of ABO, a combination of unbiased proteomics, emerging glycoproteomics, and lectin arrays targeting ABO pathways may be used to uncover which specific

![Figure 1. Schematic of ABO modification of glycoproteins and its impact on arterial thrombosis.](http://arbahajournals.org/)
peptides carry modifications. Such deep and complete profiling of glycoproteins and glycosphingolipids will allow determination of the presence, abundance, and targets of ABO and other glycan modifications in platelets, providing opportunities for clinical translation.

Furthermore, it may be useful to consider ABO as a model for the broader impact of post-translational glycan modification on platelet function. Therefore, deep glycopeptide and glycoproteomic interrogations are required to identify which proteins carry specific modifications and at which residues and domains. Such unbiased profiling will uncover many potentially biologically and clinically important glycoprotein modifications, not just those of ABH antigenicity. These modifications can be studied further, through mutagenesis in vitro and in vivo, for their impact on the function of these proteins, and in vivo for their related platelet activities in thrombosis and vascular disease. Such discovery and follow-up functional analyses will help define the effect of established ABO modifications on glycoproteins, such as glycoprotein Ia, glycoprotein Ib, and glycoprotein IIb/IIIa, as well as discover novel, and perhaps platelet-specific, glycopeptides, and glycoproteins, that modulate platelet function and arterial thrombosis.

Although ABO expression on platelet surface glycoproteins and glycosphingolipids may be of low relative abundance, these may have important functional consequences, whether via terminal modifications of glycoproteins or glycan modifications of glycolipids that are key signaling molecules in platelet-driven thrombosis at sites of atherosclerotic plaque rupture. Future targeted work will elucidate whether glycomic modifications, including ABH glycans, act on platelet functions via specific proteins and lipids or whether there is a more generalized effect of global carbohydrate type and abundance in altering platelet functions.

Conclusions

A growing body of evidence has demonstrated a strong and reproducible association between ABO blood group status and ACS, whereby non-type O blood group, compared with blood group O carriers, is associated with increased risk of CVD. Although the exact mechanism of this effect is largely unknown, several glycoproteins and glycosphingolipids on the surface of platelets are known to express ABH antigenicity. It is hypothesized that ABO modification of these glycans may affect platelet function and thrombosis. Additional studies are needed to thoroughly investigate the presence, targets, and extent of these ABO modifications and how they modulate platelet function in arterial thrombosis. A better understanding of all types of glycomic modifications and their potential impact on platelet function and thrombosis may impact future diagnostic and therapeutic targets in ACS and CVD.

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Disclosures

None.

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Several studies have demonstrated a relationship between ABO blood group and acute coronary syndromes, where O blood group has been associated with lower rates of incidence, infarct size, and mortality. Research into this relationship has focused primarily on the impact of ABO blood group on circulating von Willebrand Factor and integrins. However, platelets play a pivotal role in arterial thrombosis. Therefore, our review focuses on ABO blood type from a platelet perspective. We review the expression of ABH antigens on platelet glycoproteins and glycosphingolipids and highlight studies that examine the effect of ABO blood group on several platelet function assays. We conclude by providing perspective on future studies that can further elucidate the impact of ABO glycan modification on platelet aggregation and function. Understanding the effect of ABO blood group on platelets highlights the importance of platelet glycoprotein modifications in thrombosis, which may help inform future diagnostic and therapeutic targets.