



LUND UNIVERSITY

A and B antigen levels acquired by group O donor-derived erythrocytes following ABO-non-identical transfusion or minor ABO-incompatible haematopoietic stem cell transplantation

Hult, A K; Dykes, J H; Storry, J R; Olsson, M L

Published in:
Transfusion Medicine

DOI:
[10.1111/tme.12411](https://doi.org/10.1111/tme.12411)

2017

Document Version:
Peer reviewed version (aka post-print)

[Link to publication](#)

Citation for published version (APA):

Hult, A. K., Dykes, J. H., Storry, J. R., & Olsson, M. L. (2017). A and B antigen levels acquired by group O donor-derived erythrocytes following ABO-non-identical transfusion or minor ABO-incompatible haematopoietic stem cell transplantation. *Transfusion Medicine*, 27(3), 181-191. <https://doi.org/10.1111/tme.12411>

Total number of authors:
4

General rights

Unless other specific re-use rights are stated the following general rights apply:
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

Read more about Creative commons licenses: <https://creativecommons.org/licenses/>

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

A and B antigen levels acquired by group O donor-derived erythrocytes following ABO-nonidentical transfusion or minor ABO-incompatible haematopoietic stem cell transplantation

Annika K. Hult, Ph.D.*^{1,2}, Josefina H. Dykes, M.D., Ph.D.*¹, Assoc. Prof. Jill R. Storry, Ph.D.^{1,2}, Prof. Martin L. Olsson, M.D., Ph.D.^{1,2}

¹Clinical Immunology and Transfusion Medicine, Division of Laboratory Medicine, Office of Medical Services, Klinikgatan 21, SE-221 85 Lund, Sweden.

²Division of Hematology and Transfusion Medicine, Department of Laboratory Medicine, Lund University, BMC C14, Klinikgatan 28, SE-221 84 Lund, Sweden

* These authors contributed equally to this study

Corresponding author:

Prof. Martin L. Olsson, Division of Hematology and Transfusion Medicine, Department of Laboratory Medicine, Lund University, BMC C14, Klinikgatan 28, SE-221 84 Lund, Sweden

Phone: +46-46-2223207

Fax: +46-46-173226

E-mail: Martin.L.Olsson@med.lu.se

Running title: A and B antigens on group O donor cells

Abstract

Background and Objectives: ABO-incompatible haematopoietic stem cell transplantation (HSCT) presents a challenge to blood component transfusion. The aim of this study was to investigate the weak blood group A or B antigen expression by donor-derived group O red blood cells (RBC) observed following transfusion or minor ABO-incompatible HSCT. In addition, *in vitro* experiments were performed to elucidate possible mechanisms underlying this phenomenon.

Materials and Methods: A sensitive flow cytometry assay for the semi-quantification of RBC A/B antigen levels was used to assess patient samples and evaluate *in vitro* experiments.

Results: Analysis of blood samples from patients, originally typed as A, B and AB but recently transplanted or transfused with cells from group O donors, revealed A antigen expression on donor-derived RBC, ranging from very low levels in non-secretor individuals, to almost subgroup A_x-like profiles in group A secretors. B antigen expression was less readily detectable. *In vitro* experiments, in which group O donor RBC were incubated with i) group A/B, secretor/non-secretor donor plasma or ii) group A/B donor RBC in the absence of plasma, supported the proposed adsorption of A/B-antigen-bearing glycolipids from secretor plasma but also indicated a secretor-independent mechanism for A/B antigen acquisition as well as direct cell-to-cell transfer of ABO antigens.

Conclusion: The *in vivo* conversion of donor-derived blood group O RBC to ABO subgroup-like RBC after transfusion or minor ABO-incompatible HSCT raises the question of appropriate component selection. Based on these data, AB plasma should be transfused following ABO-incompatible HSCT.

Key words: ABO blood group antigen, red blood cell, haematopoietic stem cell transplantation, glycosphingolipids, flow cytometry

Introduction

Current guidelines for transfusion support in ABO-incompatible haematopoietic stem cell transplantation (HSCT) prescribe blood components which are compatible with both the recipient and the donor ABO groups in order to avoid hemolysis of any transfused red blood cells (RBC), the residual recipient RBC and the engrafting donor-derived RBC. From the time of complete donor erythropoietic engraftment, the recipient is generally recommended to receive blood components of donor ABO group (Apperley *et al.*, 2012; Fung *et al.*, 2014).

The stably engrafted HSCT recipient is, however, a (complete) chimaera of donor ABO blood group, intrinsically synthesized and expressed on RBC and platelets (Oriol *et al.*, 1981; Mollicone *et al.*, 1988), and recipient-group ABH antigens, ubiquitously distributed in tissues, and also in body fluids of secretors (Matsui *et al.*, 1999; Ravn *et al.*, 2000; Mueller *et al.*, 2011). Furthermore, donor-derived blood cells may exhibit low levels of recipient-group A/B antigens (Swanson *et al.*, 1971; Needs *et al.*, 1987). In the setting of a minor ABO-incompatible HSCT, where group O donor haematopoietic stem cells (HSC) are transplanted to a group A recipient, the switch to donor-group transfusion support upon complete donor engraftment will expose the recipient to antibodies directed against blood group A epitopes, expressed on vascular endothelium, carried by soluble structures in plasma and, possibly, present on circulating group O HSC-donor-derived blood cells. Extending the concept of ABO-compatible transfusion support to include the life-long chimaeric ABO status of the recipient would, thus, suggest possible implications for blood component selection.

Accumulating data indicate that infusion of plasma which contains ABO antibodies may cause rapid clearance of platelets, formation of immune complexes, endothelial cell damage and multiple organ dysfunction (Heal *et al.*, 1987; Heal *et al.*, 1993; Benjamin *et al.*, 1999; Lapierre *et al.*, 2005). Also, donor-derived ABO antibodies from passenger lymphocytes of minor ABO-incompatible HSC graft origin may induce destruction of transfused group O

RBC, possibly mediated through the adsorption of either soluble A/B antigens, A/B-antigen/antibody immune complexes or complement components onto the RBC surface (Gajewski *et al.*, 1992; Tiplady *et al.*, 2001; Worel *et al.*, 2002).

At the molecular level, the *ABO* gene encodes two different glycosyltransferases, which add either *N*-acetylgalactosamine (GalNAc) or galactose (Gal) to the H antigen precursor structure, forming A or B antigens, respectively. In haematopoietic tissue, the *FUT1* (or *H*) gene encodes a 2- α -fucosyltransferase, which synthesizes H antigen mainly on type 2 oligosaccharide acceptors, linked to proteins (approximately 90%) and lipids (approximately 10%) in the RBC membrane. In epithelial cells, the *FUT2* (also known as the secretor) gene governs the synthesis of H antigen, preferentially on type 1 precursor chains. It also determines the presence of type 1 ABH antigens in secretions, found in approximately 80% of people, so-called secretors (Daniels, 2013) (Clausen *et al.*, 1989; Morgan *et al.*, 2000; Ravn and Dabelsteen, 2000).

The acquisition *in vivo* of A/B antigens by group O RBC following transfusion or HSCT has previously been observed, using standard serological techniques (Renton *et al.*, 1962; Swanson *et al.*, 1971; Needs *et al.*, 1987; Wichmann *et al.*, 1999), and has been attributed to the adsorption from plasma onto RBC of glycosphingolipids with A/B specificity expressed on type 1 oligosaccharides (Garretta *et al.*, 1974; Tilley *et al.*, 1975; Clausen *et al.*, 1985; Jovall *et al.*, 1987). In the current study, we used a sensitive flow cytometry assay optimised in our laboratory for the semi-quantification of low levels of A/B antigens (Liu *et al.*, 2007; Hult *et al.*, 2010) to assess the extent of antigen acquisition by donor-derived group O RBC in clinical patient samples, following transfusion or HSCT. *In vitro* experiments that mimic the *in vivo* situation were performed to address the previously proposed adsorption of A/B-antigen-bearing glycosphingolipids onto RBC, and to investigate the hypothesized conversion

of H substance on the RBC surface by enzymatic action of ABO glycosyltransferases in plasma.

Material and methods

Patients

As part of the clinical monitoring, patients (n=11) of different ABO blood groups, transplanted with HSC from ABO-incompatible donors of group O or A, were evaluated by extended blood group analysis. Ethylenediamine tetracetic acid (EDTA)-anticoagulated blood samples drawn for routine blood grouping or pre-transfusion testing were analyzed and anonymized data included in the study. In addition to their HSCT, seven patients had received blood transfusions from group O blood donors within the last three months prior to testing (range: 3 - 23). Pre-transplant DNA samples were used to establish the patients' secretor status by *FUT2* genotyping and for *ABO* genotyping of selected patients. At the time of investigation, all patients were complete donor chimaeras as assessed by computer records of short tandem repeat-polymerase chain reaction analysis (data not shown).

EDTA samples were also collected from non-transplanted patients (n=15) of group A, B or AB, who had been transfused with RBC units from group O donors. The number of units received within the last three months prior to testing varied considerably (range: 1-36). Again, *FUT2* genotyping was performed to establish the patients' secretor status.

Donors

Anonymized blood samples from ABO-typed donors (n=61) collected in acid-citrate-dextrose (ACD) tubes at routine donation were used for *in vitro* experiments. No extra samples were taken for this study. Secretor status was determined by Lewis blood group phenotyping. Donors whose secretor status could not be concluded by RBC typing only, i.e. Le(a-b-), were not included. The age of the donor ACD samples varied but none of the samples used

were older than one week at the start of each experiment. Donor RBC and/or plasma were used.

Serology

ABO and Lewis phenotyping was performed with established and validated methods used at the Department of Clinical Immunology and Transfusion Medicine in Lund, Sweden.

ABO and FUT2 genotyping

Genomic typing of the *ABO* and *FUT2* loci were performed with established and validated methods used at the Nordic Reference Laboratory for Genomic Blood Group Typing (NRLGBT) in Lund, Sweden. Polymerase chain reaction with allele-specific primers (PCR-ASP) was used (Hosseini-Maaf *et al.*, 2007).

Flow cytometry

Flow cytometry was performed as previously described (Liu, Sulzenbacher *et al.*, 2007; Hult and Olsson, 2010). Samples of the following ABO phenotypes (genotypes) were included as controls in each run: A₂, B, O, A_x (*ABO*AW30.01/O.01.01*) and B_w (*ABO*BW.03/O.01.01*). ABO terminology according to ISBT is used throughout this paper (www.isbtweb.org).

In vitro experiments

Group O RBC were mixed with either plasma or RBC from donors of ABO groups A₁, A₂, or B, both secretors and non-secretors (Fig.1). Group O RBC mixed with autologous group O plasma or RBC, were included in each experiment as negative controls.

Investigating plasma-to-cell transfer of ABO antigens

ACD tubes were centrifuged at 1500 x g for 10 minutes, to separate plasma and RBCs. Washed, packed group O RBC were suspended 1:5 in group A₁/B/O plasma in appropriately labelled glass tubes, sealed and placed in either 4°C, room temperature (RT), 37°C or 37°C with constant mixing, for up to 16 days.

Papain-treated RBC were used in two experiments. Papain-treatment was performed according to standard blood bank practice (Fung *et al.*, 2014). In preparation for flow cytometric analysis, 25 µL RBC from every tube were transferred to a new glass tube, washed three times in PBS and 10 µL packed RBC were re-suspended in 400 µL PBS.

Investigating cell-to-cell transfer of ABO antigens

ACD tubes were centrifuged at 1500 x g for 10 minutes, plasma and RBC were separated. RBC were washed three times in PBS. Packed group O RBC were mixed 1:4 with packed A₁/A₂/B/O RBC in 1 mL Eppendorf tubes, sealed and placed in an incubator with constant gentle mixing at 37°C, for up to four days.

In one experiment, cell-cell mixes diluted with 200 µL of PBS or A/B plasma to a hematocrit of approximately 45%, aiming to create a more *in-vivo*-like environment, were incubated in parallel with the undiluted cell-cell mixes. Cells were prepared for flow cytometric analysis as described above.

Detection of A and B glycosyltransferase activity in plasma

Twenty-five microliters of a 10 % suspension of washed group O RBC were incubated with 190 µL of plasma from group A₁/A₂/B/O, non-secretor individuals at 37°C for up to 48 hours under the following conditions: 0.35 mM UDP-GalNAc (Uridine 5'-diphospho-N-acetylgalactosamine disodium salt, Product#U5252, Sigma-Aldrich, Sweden) or UDP-Gal

(Product# U4500, Sigma-Aldrich, Sweden); 10 mM MnCl₂ (BioChemika, product#48975, Sigma-Aldrich, Sweden) in a total volume of 250 µL (adapted from Schenkel-Brunner *et al.*, 1969). In one experiment, inactivation of glycosyltransferase activity in plasma was attempted with three different approaches: i) Heat inactivation using ACD plasma incubated for 10 minutes at 56°C; ii) using plasma from blood drawn in EDTA tubes, and iii) using ACD plasma supplemented with an excess of EDTA. EDTA is a well-known chelating agent and complex binding of the Mn²⁺ ions required for ABO transferase activity was anticipated. Cells were prepared for flow cytometric analysis as described above.

Results

Transplanted patients

A total of 11 patients who had been transplanted with ABO-incompatible HSC were tested. Seven patients were also transfused with group O RBC. Repeat samples were available from four patients. The results are summarized in Table 1.

When donor-derived group O RBC were tested with anti-A, an increase in mean fluorescence intensity (MFI) compared to group O RBC controls were observed in all patients but one, who had received multiple blood transfusion on consecutive days just before blood sampling. The A antigen levels ranged from low but well detectable to higher, almost subgroup A_x-like profiles. The mean MFI values with anti-A were higher in secretors than in the only group A non-secretor patient available for testing (Fig. 2a and b). Two patients, who were originally group A secretors and had similar transplant and transfusion histories but very different MFI, were genetically defined as *ABO**A2.01/O.01.02 and *ABO**A1.01/O.02, respectively (Fig. 2e). Two group B secretor patients and one group AB secretor patient showed no detectable B antigen on donor-derived group O RBC (Fig. 2d), although the group AB patient exhibited a weak A antigen expression (Fig. 2c).

Non-transplanted but transfused patients

A total of 15 patients, secretors and non-secretors of group A, B or AB transfused with RBC from group O donors were tested. Repeat samples were available in six patients. The results are summarized in Table 2. All blood group A patients showed an increase in MFI, greater in group A secretors (Fig. 2f), than in group A non-secretors (Fig. 2g). In transfused group B secretor patients, as opposed to the single group B non-secretor tested, a slight rise in MFI was observed compared to group O RBC controls. A particularly informative flow cytometric pattern was observed in a group A secretor patient (Fig. 2h). Three distinct cell populations

were displayed, with MFI values corresponding to A antigen levels of i) normal group A RBC, ii) donor-derived group O RBC circulating in group A secretors and iii) the group O RBC control. This patient had been transfused with ten units of group O RBC within the last three weeks, including one unit just prior to blood sampling, indicating that time in circulation for transfused group O RBC correlates with A antigen levels adsorbed. In one group A secretor patient, transfused with three group O RBC units in five consecutive days, repeat samples were available at two, four and eight weeks and a rise in MFI of the donor-derived O RBC over time was observed.

In vitro experiments

Investigating plasma-to-cell transfer of ABO antigens

In an attempt to mimic *in vitro* the circulating donor-derived group O RBC following transfusion or minor ABO-incompatible HSCT *in vivo*, normal group O RBC were mixed with secretor or non-secretor plasma from group A₁ and B donors. Group O plasma was used as a negative control.

When tested with anti-A, all group O RBC incubated with group A₁ plasma at 37°C or RT showed an increase in MFI over time compared to the group O plasma control (Fig. 3a). A greater increase in MFI, corresponding to a higher level of A antigen, was observed when group O RBC were incubated with group A₁ secretor plasma compared to group A₁ non-secretor plasma. Incubating RBC/plasma mixes with or without constant mixing (at 37°C) did not influence the increase of MFI, whereas incubation at 4°C gave no rise in MFI compared to the O plasma control. Group O RBC incubated with group B secretor or non-secretor plasma and tested with anti-B showed no rise in MFI over time compared to the group O plasma control (Fig. 3b).

Investigating cell-to-cell transfer of ABO antigens

Washed and packed group O RBC, mimicking donor-derived group O RBC, were mixed with washed and packed RBC from group A₁, A₂ and B, secretor and non-secretor donors and incubated at 37°C with constant mixing. Group O RBC were used as a negative control.

When group O RBC incubated with group A₁ RBC were tested with anti-A, a rise in MFI was observed equivalent to the MFI seen in the naturally-occurring ABO subgroup A_x. When group O RBC incubated with group A₂ or B RBC were tested with anti-A or anti-B, respectively, the rise in MFI was not as apparent as in group O RBC/A₁ RBC mixes but still clearly detectable.

A difference in MFI between cell-cell mixes including secretors *vs.* non-secretors was also clearly shown for group A₁ and B mixes (Fig. 4a and b). No apparent difference was seen with group A₂ secretors versus non-secretors.

Attempting to mimic a more physiologic RBC concentration environment, PBS or group A/B non-secretor plasma was added to the RBC mixes. The rise in MFI was not as dramatic as in the undiluted RBC mixes but still detectable when PBS was added. When non-secretor AB plasma was added to the group O RBC/A₁ RBC mixes the rise in MFI was very discrete (Fig. 4c) and with the group O RBC/A₂ or B RBC mixes a rise in MFI was not detectable.

Functional detection of A and B glycosyltransferase activity in plasma

Substrate (UDP-GalNAc for A-glycosyltransferase [GTA] and UDP-Gal for B-glycosyltransferase [GTB]) and MnCl₂ were added to group O RBC mixed with group A₁, A₂ or B non-secretor plasma and incubated at 37°C. When incubated with the appropriate A or B antigens were readily detectable on the group O RBC after 4 hours. MFI was higher for group O RBC incubated with group A₁ and B plasma than for group O RBC incubated with group A₂ plasma (Fig. 4d-f). The MFI increased with time and after 48 hours group O RBC

incubated with group A₁ and B plasma expressed A and B antigen at a level almost equivalent to normal group A₂ and B RBC. When group O RBC were incubated with group B plasma, UDP-GalNAc and MnCl₂ they showed a very slight rise in MFI compared to the O plasma control, when tested with anti-A. The low levels of A antigen detected on the group O RBC were consistent with the small amounts of A antigen normally detectable on common group B RBC (Goldstein *et al.*, 1989).

When either of the reagents (donor substrate, MnCl₂ or A/B plasma) was excluded or group O plasma was used instead of group A/B plasma no change in MFI compared to the group O control RBC was observed. Complete inactivation of the glycosyltransferases was achieved only by the addition of an excess of EDTA to ACD plasma. Inactivated A₁ plasma was incubated with group O RBC, UDP-GalNAc and MnCl₂ and no A antigens could be detected with anti-A.

Discussion

In this study, we demonstrate and semi-quantify the *in vivo* conversion of donor-derived blood group O RBC to ABO-subgroup-like RBC following transfusion to ABO-nonidentical recipients or after minor ABO-incompatible HSCT. Utilizing a sensitive flow cytometry protocol, donor group O RBC were found to express variable levels of acquired antigen, ranging from very small amounts in non-secretor individuals to subgroup A_x-like profiles, in group A₁ secretors. Our findings support the major role of A/B antigen adsorption from secretor plasma, but also indicate that secretor status is not an absolute prerequisite for the *in vivo* conversion of group O RBC.

Detectable levels of antigen adsorbed from secretor plasma onto group O RBC may increase over time as demonstrated in the *in vitro* experiments (Fig. 3a) and illustrated by the characteristic flow cytometric patterns of group A secretor individuals repeatedly transfused with group O RBC (Fig. 2f). Also, the time course of antigen adsorption onto RBC may be influenced by inhibiting factors in plasma (Tilley *et al.*, 1975), suggesting competition by plasma lipoproteins for lipid uptake which may have influenced the flow cytometric pattern observed in Fig. 4c.

The marked difference in detectable levels of adsorbed antigen between secretor individuals of different ABO blood groups reflects a variable amount of soluble antigen available in plasma, governed by the complex interaction between the *ABO* and *FUT1* gene, the secretor gene (*FUT2*) and the Lewis gene (*FUT3*), and is influenced by allelic variants at these loci. The enzymes encoded by *ABO* and *FUT3* compete for the common type 1 H acceptor substrate to produce A/B antigens or difucosylated Le^b antigen (Watkins *et al.*, 1988; Henry *et al.*, 1995). The enzyme produced by the A¹ allele of the *ABO* locus is more efficient than its A² allelic variant in competing with the Lewis enzyme for type 1 H acceptor substrate. Accordingly, among group A secretors of the Le(a-b+) phenotype, levels of soluble A or

ALe^b antigen are higher in A₁ than A₂ individuals (Holburn *et al.*, 1974; Tilley *et al.*, 1975; Achermann *et al.*, 2005). In two secretor patients genetically defined as *ABO**A1.01/O.02 and *ABO**A2.01/O.01.02, respectively (Fig. 2e), we found a clear difference in A antigen levels on donor-derived group O RBC, corresponding to the quantitative difference in A₁- and A₂-glycosyltransferase activity when it comes to synthesis of A type 1 (Schachter *et al.*, 1971; Schenkel-Brunner *et al.*, 1973). A possible effect of secretor gene zygosity was suggested by the finding in our study that patients who typed homozygous for c.428G in their *FUT2* genes (i.e. homozygous for active secretor alleles, previously referred to as *Se*), expressed comparatively high levels of original blood group A/B antigens on donor-derived group O RBC. In another study, however, levels of soluble ABO blood group substance in plasma were not influenced by the homozygous expression of the A¹, A² or *Se* alleles, respectively (Achermann *et al.*, 2005).

In non-secretor plasma, A/B antigens are found, albeit in small quantities, on type 2 carbohydrate chains linked to glycoproteins and glycosphingolipids, and are presumed to emanate from endothelial or haematopoietic cells (Hostrup, 1962; Holburn 1974; Tilley *et al.*, 1975; Le Pendu *et al.*, 1982). Lactosylceramide, which is the major glycosphingolipid precursor on RBCs (Clausen *et al.*, 1989), is also expressed in endothelial cells. In plasma, glycosphingolipids are associated with lipoproteins and may, thus, be exchanged between cells and lipoproteins, or vice versa, via shedding and/or receptor-mediated endocytosis (Chatterjee, 1998). In the recipient of a minor ABO-incompatible HSCT (group O donor to group A recipient, Fig. 2b), the endothelium is, thus, a plausible source of type 2 A antigen available for transfer to transfused group O RBC. In a transfused group A, non-secretor patient (Fig. 2g), the haematopoietic tissue may contribute to the total amount of lipid-linked type 2 A antigen available for uptake. A possible mechanism also for direct membrane glycolipid exchange between adjacent RBC was suggested by the *in vitro* experiments (Fig. 4

a-c), most prominent when RBC were close to each other. Among the plasma glycoproteins known to carry A/B antigens on *N*-linked oligosaccharide chains, endothelium-derived vWF and a minor portion (10%) of α_2 -macroglobulin (Matsui *et al.*, 1993; Matsui *et al.*, 1999) circulate in plasma independently of secretor status. Available data, however, suggest that these glycoproteins are not of significant importance to *in vivo* RBC A/B antigen expression (Kirschkamp *et al.*, 2008; Santizo *et al.*, 2009).

The possible mechanism of H substance conversion on the surface of donor-derived group O RBC, by enzymatic action of GTA/GTB in non-secretor plasma, was hypothesized and successfully demonstrated *in vitro* by adding an excess of the appropriate donor sugar substrate. The A/B-enzymes are present in plasma irrespectively of secretor status, with only a minor part originating from haematopoietic tissue (Schachter 1971; Yoshida *et al.*, 1980), and are generally considered incapable of enzymatic activity on the RBC surface, due to insufficient extracellular concentrations of donor-sugar nucleotides (Varki *et al.*, 1999). Also, in the recipient of a minor ABO-incompatible HSCT, inhibiting antibodies directed against endogenous GTA/GTB may completely abolish enzymatic activity in plasma (Barbolla *et al.*, 1988). However, recent reports have shown evidence for extrinsic glycosylation driven by circulating extracellular glycosyltransferases where the donor sugar substrates are provided by activated platelets (Lee *et al.*, 2014; Lee-Sundlov *et al.*, 2017).

The difficulties in this study to detect adsorption of B antigen from secretor plasma by donor group O RBC following transplantation (Table 1, Fig. 2d) or transfusion (Table 2), as well as in the *in vitro* experiments (Fig. 3b), may either suggest that the GTB is a poorer competitor to the Lewis enzyme for H type 1 substrate in secretions than GTA, or that BLe^b antigen is preferentially formed but not detected. Notably, a reduced level of A antigen on donor group O RBC was observed in group A₁B secretors compared to group A₁ secretors (Table 1 and 2),

indicating GTB activity resulting in conversion of H type 1 antigen. The monoclonal antibodies used in this study, anti-A clone ES-15 and anti-B clone 9621A8, were specifically selected for their high sensitivity and ability to detect native ABO subgroups (Hult *et al.*, 2010) and remnant A/B antigens after exoglycosidase treatment (Liu *et al.*, 2007) by flow cytometry. However, in more recent experiments, using clone ES-15 and clone 9621A8 in flow cytometry evaluation of RBC modified with synthetic glycolipid A/B constructs (KODE technology), we found that a transformation with five times more B construct than A construct was required to create RBC with equivalent serological and flow cytometric features (Hult *et al.*, 2012). This phenomenon has shown to be consistent when either monoclonal or human polyclonal antibodies are tested against both natural and synthetic B antigen, and is believed to be due to the structure of the B antigen, which has an inherently lower affinity for specific antibody, in contrast to the A antigen, which has the *N*-acetyl protrusion on its terminal sugar. Notwithstanding, in contrast to the scarce amount of B antigen found to be adsorbed from secretor plasma, the co-incubation of group O and B RBC in the absence of plasma induced readily detectable levels of B antigen on donor group O RBC (Fig. 4b), suggesting a transfer of B type 2 glycolipids. Notably, this may point to a preference of the anti-B clone 9621A8 for type 2 based B antigen, although the degree of antibody specificity for type 1 versus type 2 oligosaccharides was not investigated in this study. However, the antibody is known to react in ELISA with synthetically produced group B oligosaccharides of both type 1 and 2 while BLe^b structures were apparently not tested (personal communication from the manufacturer of the reagent). It is possible that some of the antigen adsorbed onto donor cells is indeed of BLe^b type, which may explain why the anti-B used does not react readily.

The transient course of donor-derived A/B antibody titres and the apparent escape of endothelial cells from GvHD in minor ABO-incompatible HSCT, may be attributed to

antibody adsorption, induction of donor lymphocyte tolerance or endothelial cell accommodation (Takahashi, 2005; Stussi *et al.*, 2006). In contrast, repeat transfusion of donor ABO-type plasma and platelet components may cause immune-complex formation, multi-organ dysfunction and impaired survival (Benjamin *et al.*, 1999; Heal *et al.*, 2005). In this setting, circulating donor-derived RBC have an important role in CR1-receptor mediated clearance of immune-complexes (Reinagel *et al.*, 1997) but are, as shown here, also potential targets for direct ABO antibody binding and possibly hemolysis.

In this study, we demonstrate and characterize the *in vivo* conversion of donor-derived group O RBC to ABO subgroup-like RBC following transfusion or HSCT, utilizing a sensitive flow cytometer assay that enables the distinction between HSC-donor-derived RBC, expressing low levels of acquired A/B antigen, and reappearing RBC of recipient origin, which may herald relapse or HSC graft rejection (David *et al.*, 1999). Our findings confirm the major role of A/B antigen adsorption from secretor plasma, but also indicate an additional, secretor-independent mechanism for A/B antigen acquisition. In a clinical context, this study provides additional support for the proposed selection of plasma components compatible with both donor and recipient ABO blood group, (Heal *et al.*, 2005; O'Donghaile *et al.*, 2012) also beyond the time of complete HSC engraftment. It can be noted that certain source still recommend blood components of the donor's ABO group, once a routine grouping shows that the cells appear to type as the donor (Fung *et al.*, 2014) but our study shows that a highly sensitive flow cytometric analysis is valuable for establishing the recipient's true blood group status."

Author Contributions

AKH performed the experiments. AKH, JHD, JRS and MLO designed experiments and interpreted data. AKH, JHD and MLO wrote the paper, JRS reviewed and revised it, and all authors approved the final version.

Financial Disclosure Statement

The authors have no financial conflicts in relation to the presented study.

Acknowledgements

This study was supported by the Swedish Research Council (grant no. 14251 to MLO), governmental ALF research grants to Lund University Hospital and Labmedicin Skåne (JRS, MLO, JHD), the Medical Faculty at Lund University (AKH, MLO) and the Skåne County Council's Research and Development foundation, Sweden (MLO).

References

- Achermann, F.J., Julmy, F., Gilliver, L.G., Carrel, T.P. and Nydegger, U.E. (2005). Soluble type A substance in fresh-frozen plasma as a function of ABO and Secretor genotypes and Lewis phenotype. *Transfusion and Apheresis Science* **32**, 255-262.
- Apperley, J., Carreras, E., Gluckman, E. and Masszi, T. (2012). *The EBMT Handbook*, European School of Haematology, Paris Cedex.
- Barbolla, L., Mojena, M. and Bosca, L. (1988). Presence of antibody to A- and B-transferases in minor incompatible bone marrow transplant. *British Journal of Haematology* **70**, 471-476.
- Benjamin, R.J. and Antin, J.H. (1999). ABO-incompatible bone marrow transplantation: the transfusion of incompatible plasma may exacerbate regimen-related toxicity. *Transfusion* **39**, 1273-1274.
- Chatterjee, S. (1998). Sphingolipids in atherosclerosis and vascular biology. *Arterioscler Arteriosclerosis, Thrombosis, and Vascular Biology* **18**, 1523-1533.
- Clausen, H. and Hakomori, S. (1989). ABH and related histo-blood group antigens; immunochemical differences in carrier isotypes and their distribution. *Vox Sanguinis* **56**, 1-20.
- Clausen, H., Levery, S.B., McKibbin, J.M. and Hakomori, S. (1985). Blood group A determinants with mono- and difucosyl type 1 chain in human erythrocyte membranes. *Biochemistry* **24**, 3578-3586.
- Daniels, G. (2013). *Human Blood Groups*, 3rd edition, Wiley-Blackwell, Oxford.
- David, B., Bernard, D., Navenot, J.M., Muller, J.Y. and Blanchard, D. (1999). Flow cytometric monitoring of red blood cell chimerism after bone marrow transplantation. *Transfusion Medicine* **9**, 209-217.
- Fung, M.K., Grossman, B.J., Hillyer, C.D. and Westhoff, C.M. (2014). *AABB Technical Manual*, 18th edition, AABB (American Association of Blood Banks).
- Gajewski, J.L., Petz, L.D., Calhoun, L., O'Rourke, S., Landaw, E.M., Lyddane, N.R., Hunt, L.A., Schiller, G.J., Ho, W.G. and Champlin, R.E. (1992). Hemolysis of transfused group O red blood cells in minor ABO-incompatible unrelated-donor bone marrow transplants in patients receiving cyclosporine without posttransplant methotrexate. *Blood* **79**, 3076-3085.
- Garretta, M., Muller, A., Courouce-Pauty, A.M. and Moullec, J. (1974). In vitro transformation of group O red blood cells by A and B serum substances. *Biomedicine* **21**, 114-118.
- Goldstein, J., Lenny, L., Davies, D. and Voak, D. (1989). Further evidence for the presence of A antigen on group B erythrocytes through the use of specific exoglycosidases. *Vox Sanguinis* **57**, 142-146.
- Heal, J.M., Blumberg, N. and Masel, D. (1987). An evaluation of crossmatching, HLA, and ABO matching for platelet transfusions to refractory patients. *Blood* **70**, 23-30.
- Heal, J.M., Liesveld, J.L., Phillips, G.L. and Blumberg, N. (2005). What would Karl Landsteiner do? The ABO blood group and stem cell transplantation. *Bone Marrow Transplant* **36**, 747-755.
- Heal, J.M., Rowe, J.M., McMican, A., Masel, D., Finke, C. and Blumberg, N. (1993). The role of ABO matching in platelet transfusion. *European Journal of Haematology* **50**, 110-117.
- Henry, S., Oriol, R. and Samuelsson, B. (1995). Lewis histo-blood group system and associated secretory phenotypes. *Vox Sanguinis* **69**, 166-182.

- Holburn, A.M. and Masters, C.A. (1974). The radioimmunoassay of serum and salivary blood group A and Lea glycoproteins. *British Journal of Haematology* **28**, 157-167.
- Hosseini-Maaf, B., Hellberg, A., Chester, M.A. and Olsson, M.L. (2007). An extensive PCR-ASP strategy for clinical ABO blood group genotyping that avoids potential errors caused by null, subgroup and hybrid alleles. *Transfusion* **47**, 2110-2125.
- Hostrup, H. (1962). A and B blood group substances in the serum of normal subjects. *Vox Sanguinis* **7**, 704-721.
- Hult, A.K., Frame, T., Chesla, S., Henry, S. and Olsson, M.L. (2012). Flow cytometry evaluation of red blood cells mimicking naturally occurring ABO subgroups after modification with variable amounts of function-spacer-lipid A and B constructs. *Transfusion* **52**, 247-251.
- Hult, A.K. and Olsson, M.L. (2010). Many genetically defined ABO subgroups exhibit characteristic flow cytometric patterns. *Transfusion* **50**, 308-323.
- Jovall, P.A., Lindstrom, K., Pascher, I., Pimlott, W. and Samuelsson, B.E. (1987). Identification of a blood group A active hexaglycosylceramide with a type 1 carbohydrate chain in plasma of an A1 Le(a-b-) secretor. *Archives of Biochemistry and Biophysics* **257**, 409-415.
- Kirschkamp, T., Schmid-Schonbein, H., Weinberger, A. and Smeets, R. (2008). Effects of fibrinogen and alpha2-macroglobulin and their apheretic elimination on general blood rheology and rheological characteristics of red blood cell aggregates. *Therapeutic Apheresis and Dialysis* **12**, 360-367.
- Lapierre, V., Mahe, C., Auperin, A., Stambouli, F., Oubouzar, N., Tramalloni, D., Benhamou, E., Tiberghien, P. and Hartmann, O. (2005). Platelet transfusion containing ABO-incompatible plasma and hepatic veno-occlusive disease after hematopoietic transplantation in young children. *Transplantation* **80**, 314-319.
- Le Pendu, J., Lemieux, R.U., Lambert, F., Dalix, A.M. and Oriol, R. (1982). Distribution of H type 1 and H type 2 antigenic determinants in human sera and saliva. *The American Journal of Human Genetics* **34**, 402-415.
- Lee-Sundlov, M.M., Ashline, D.J., Hanneman, A.J., Grozovsky, R., Reinhold, V.N., Hoffmeister, K.M. and Lau, J.T. (2017). Circulating blood and platelets supply glycosyltransferases that enable extrinsic extracellular glycosylation. *Glycobiology* **27**, 188-198.
- Lee, M.M., Nasirikenari, M., Manhardt, C.T., Ashline, D.J., Hanneman, A.J., Reinhold, V.N. and Lau, J.T. (2014). Platelets support extracellular sialylation by supplying the sugar donor substrate. *The Journal of Biological Chemistry* **289**, 8742-8748.
- Liu, Q.P., Sulzenbacher, G., Yuan, H., Bennett, E.P., Pietz, G., Saunders, K., Spence, J., Nudelman, E., Levery, S.B., White, T., Neveu, J.M., Lane, W.S., Bourne, Y., Olsson, M.L., Henrissat, B. and Clausen, H. (2007). Bacterial glycosidases for the production of universal red blood cells. *Nature Biotechnology* **25**, 454-464.
- Matsui, T., Fujimura, Y., Nishida, S. and Titani, K. (1993). Human plasma alpha 2-macroglobulin and von Willebrand factor possess covalently linked ABO(H) blood group antigens in subjects with corresponding ABO phenotype. *Blood* **82**, 663-668.
- Matsui, T., Shimoyama, T., Matsumoto, M., Fujimura, Y., Takemoto, Y., Sako, M., Hamako, J. and Titani, K. (1999). ABO blood group antigens on human plasma von Willebrand factor after ABO-mismatched bone marrow transplantation. *Blood* **94**, 2895-2900.
- Mollicone, R., Caillard, T., Le Pendu, J., Francois, A., Sansonetti, N., Villarroja, H. and Oriol, R. (1988). Expression of ABH and X (Lex) antigens on platelets and lymphocytes. *Blood* **71**, 1113-1119.
- Morgan, W.T. and Watkins, W.M. (2000). Unravelling the biochemical basis of blood group ABO and Lewis antigenic specificity. *Glycoconjugate Journal* **17**, 501-530.

- Mueller, R.J., Stussi, G., Puga Yung, G., Nikolic, M., Soldini, D., Halter, J., Meyer-Monard, S., Gratwohl, A., Passweg, J.R., Odermatt, B., Schanz, U., Biedermann, B.C. and Seebach, J.D. (2011). Persistence of recipient-type endothelium after allogeneic hematopoietic stem cell transplantation. *Haematologica* **96**, 119-127.
- Needs, M.E., McCarthy, D.M. and Barrett, J. (1987). ABH and Lewis antigen and antibody expression after bone marrow transplantation. *Acta Haematologica* **78**, 13-16.
- O'Donghaile, D., Kelley, W., Klein, H.G. and Flegel, W.A. (2012). Recommendations for transfusion in ABO-incompatible hematopoietic stem cell transplantation. *Transfusion* **52**, 456-458.
- Oriol, R., Le Pendu, J., Sparkes, R.S., Sparkes, M.C., Crist, M., Gale, R.P., Terasaki, P.I. and Bernoco, M. (1981). Insights into the expression of ABH and Lewis antigens through human bone marrow transplantation. *The American Journal of Human Genetics* **33**, 551-560.
- Ravn, V. and Dabelsteen, E. (2000). Tissue distribution of histo-blood group antigens. *Acta Pathologica, Microbiologica et Immunologica Scandinavica* **108**, 1-28.
- Reinagel, M.L., Gezen, M., Ferguson, P.J., Kuhn, S., Martin, E.N. and Taylor, R.P. (1997). The primate erythrocyte complement receptor (CR1) as a privileged site: binding of immunoglobulin G to erythrocyte CR1 does not target erythrocytes for phagocytosis. *Blood* **89**, 1068-1077.
- Renton, P.H. and Hancock, J.A. (1962). Uptake of A and B antigens by transfused group O erythrocytes. *Vox Sanguinis* **7**, 33-38.
- Santizo, F., Zenteno, E., Pina-Canseco, S., Hernandez-Cruz, P., Cruz, M.M., Mayoral, L.P., Perez-Campos, E. and Martinez-Cruz, R. (2009). Lectin activity of the coagulation factor VIII/von Willebrand complex. *The Tohoku Journal of Experimental Medicine* **217**, 209-215.
- Schachter, H. and Michaels, M.A. (1971). A quantitative difference in the activity of blood group A-specific N-acetylgalactosaminyltransferase in serum from A 1 and A 2 human subjects. *Biochemical and Biophysical Research Communications* **45**, 1011-1018.
- Schenkel-Brunner, H. and Tuppy, H. (1969). Enzymatic conversion of human O into A erythrocytes and of B into AB erythrocytes. *Nature* **223**, 1272-1273.
- Schenkel-Brunner, H. and Tuppy, H. (1973). Enzymatic conversion of human blood-group-O erythrocytes into A 2 and A 1 cells by -N-acetyl-D-galactosaminyl transferases of blood-group-A individuals. *European Journal of Biochemistry* **34**, 125-128.
- Stussi, G., Halter, J., Schanz, U. and Seebach, J.D. (2006). ABO-histo blood group incompatibility in hematopoietic stem cell and solid organ transplantation. *Transfusion and Apheresis Science* **35**, 59-69.
- Swanson, J., Crookston, M.C., Yunis, E., Azar, M., Gatti, R.A. and Good, R.A. (1971). Lewis substance in a human marrow-transplantation chimaera. *Lancet* **1**, 396.
- Takahashi, K. (2005). A new concept of accommodation in ABO-incompatible kidney transplantation. *Clinical Transplantation* **19 Suppl 14**, 76-85.
- Tilley, C.A., Crookston, M.C., Brown, B.L. and Wherrett, J.R. (1975). A and B and A1Leb substances in glycosphingolipid fractions of human serum. *Vox Sanguinis* **28**, 25-33.
- Tiplady, C.W., Fitzgerald, J.M., Jackson, G.H., Conn, J.S. and Proctor, S.J. (2001). Massive haemolysis in a group A recipient of a group O peripheral blood stem cell allogeneic transplant. *Transfusion Medicine* **11**, 455-458.
- Varki, A., Cummings, R., Esko, J., Freeze, H., Hart, G. and Marth, J. (1999). *Essentials of Glycobiology*, Cold Spring Harbor Laboratory Press Cold Spring Harbor, NY
- Watkins, W.M., Greenwell, P., Yates, A.D. and Johnson, P.H. (1988). Regulation of expression of carbohydrate blood group antigens. *Biochimie* **70**, 1597-1611.

- Wichmann, M.G., Haferlach, T., Suttorp, M., Zangh, Y. and Neppert, J. (1999). Can Blood Group O Red Cells of Donor Origin Acquire Weak Group A Reactivity through Serum A Transferase of the Recipient after Bone Marrow Transplantation? *Infusionstherapie und Transfusionsmedizin* **23**, 29-31.
- Worel, N., Greinix, H.T., Keil, F., Mitterbauer, M., Lechner, K., Fischer, G., Mayr, W., Hocker, P. and Kalhs, P. (2002). Severe immune hemolysis after minor ABO-mismatched allogeneic peripheral blood progenitor cell transplantation occurs more frequently after nonmyeloablative than myeloablative conditioning. *Transfusion* **42**, 1293-1301.
- Yoshida, A., Schmidt, G.M., Blume, K.G. and Beutler, E. (1980). Plasma blood group glycosyltransferase activities after bone marrow transplantation. *Blood* **55**, 699-701.

Table 1. Semi-quantification of A/B antigen levels on donor-derived group O RBC following HSCT

Original ABO group and secretor status	Patients		Relative mean MFI ¹ of donor-derived O RBC ²	
	HSCT with donor of blood group O	HSCT with donor of blood group A	Anti-A	Anti-B
A secretor	7 ³	-	2.9	-
AB secretor	1	-	2.6	1.0
B secretor	-	2	1.9	1.0
A non-secretor	1	-	1.5	-

HSCT = Haematopoietic stem cell transplantation; MFI = Mean fluorescence intensity

¹ Given as the ratio of mean MFI of donor-derived O RBC and mean MFI of O control RBC

² Blood group O RBC derived from donor of transplanted HSC or donor of transfused blood units. The number of units transfused within the last three months prior to testing ranged from three to 23 in seven of the transplanted patients.

³ Up to four consecutive samples were available from four of the seven A secretor patients for analysis and inclusion in the calculation of relative mean MFI.

Table 2. Semi-quantification of A/B antigen levels on donor-derived group O RBC following transfusion

Patients		Relative mean MFI ¹ of donor-derived O RBC ²	
ABO group and secretor status	Numbers ³	Anti-A	Anti-B
A secretor	7	2.3	-
AB secretor	1	1.9	1.1
B secretor	4	-	1.1
A non-secretor	2	1.7	-
B non-secretor	1	-	1.0

MFI = Mean fluorescence intensity

¹Given as the ratio of mean MFI of donor-derived O RBC and mean MFI of O control RBC

² The number of units transfused within the last three months prior to testing ranged from one to 36

³ Up to four consecutive samples were available from six of the 15 patients for analysis and inclusion in the calculation of relative mean MFI.

Figure 1

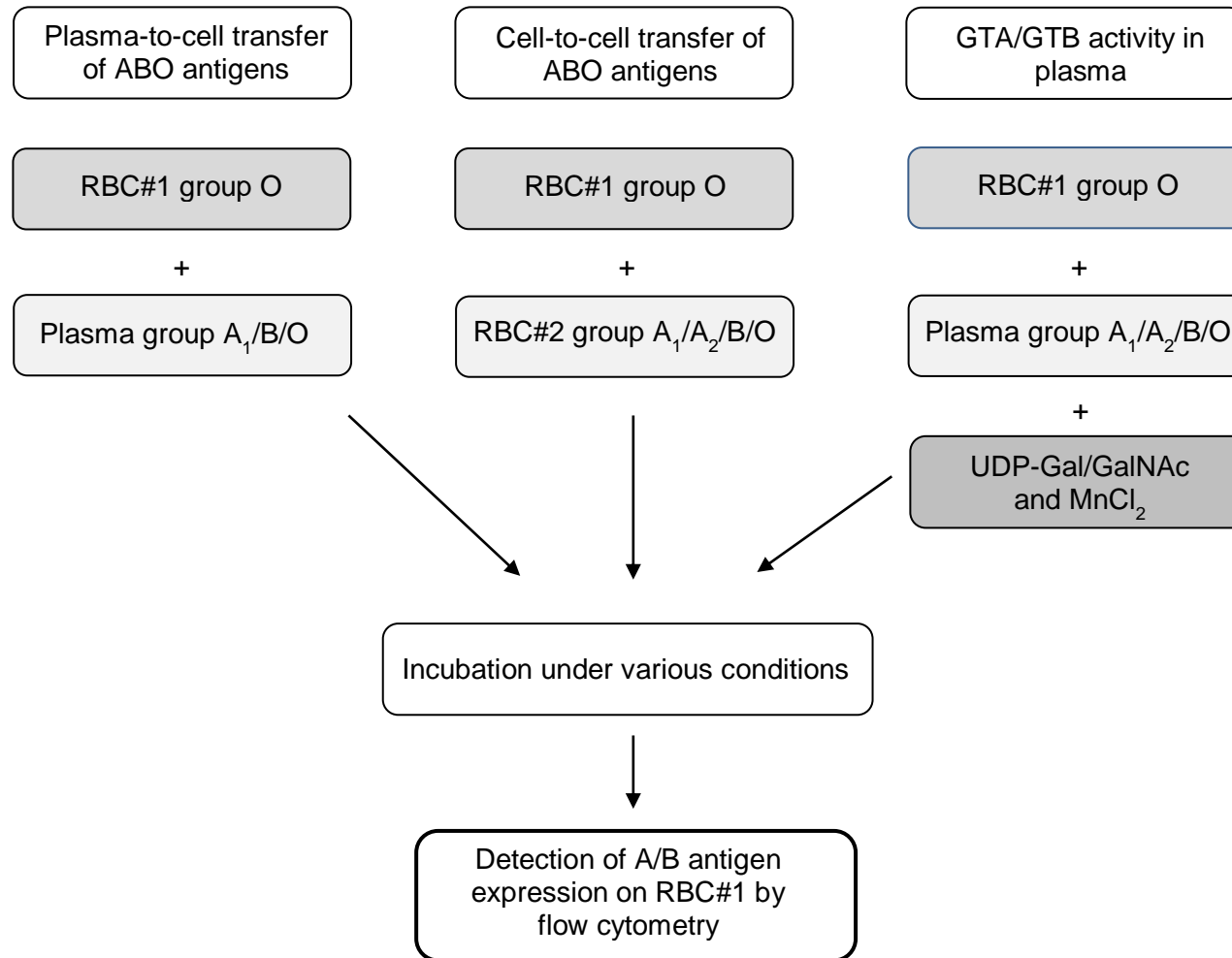


Figure 2.

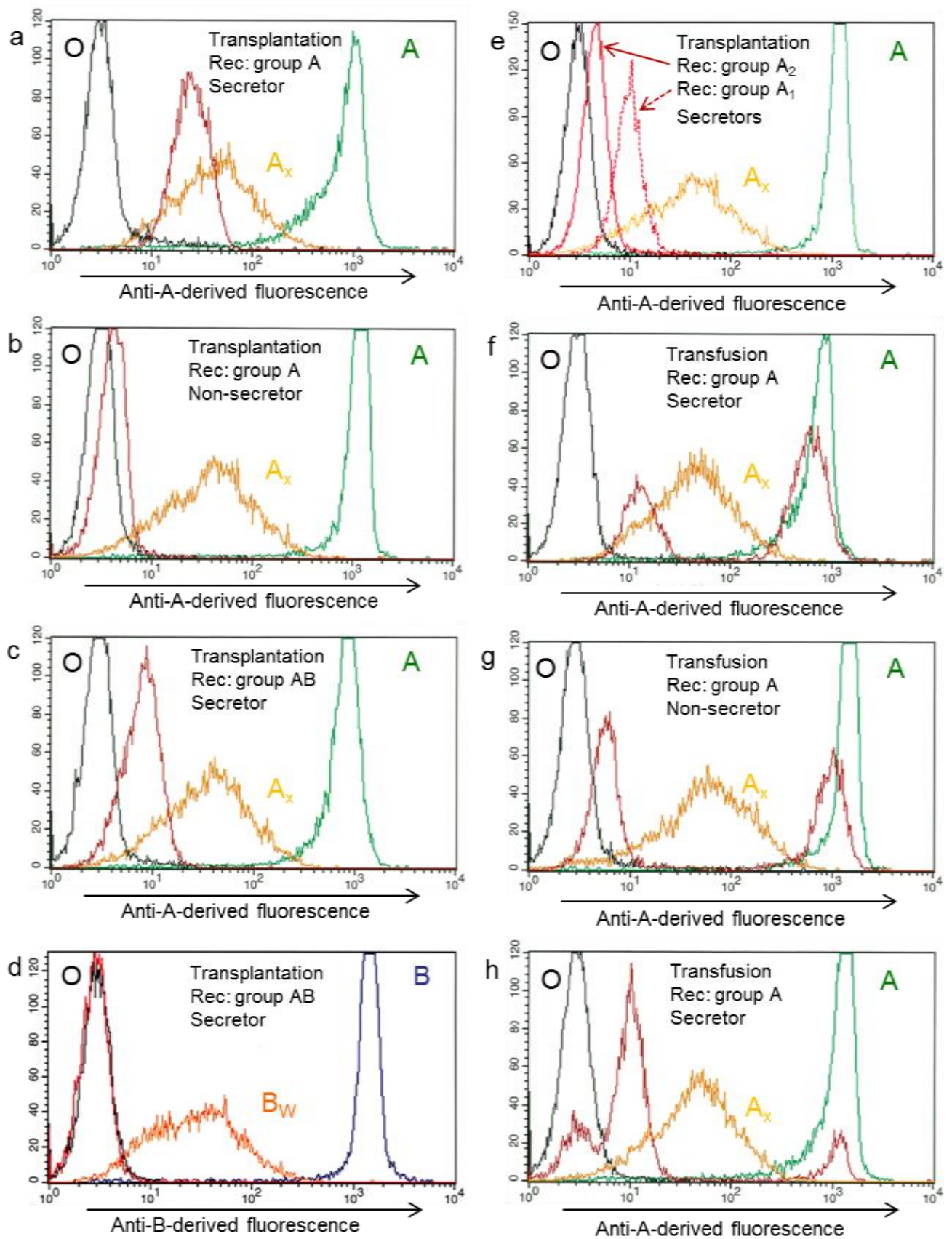


Figure 3

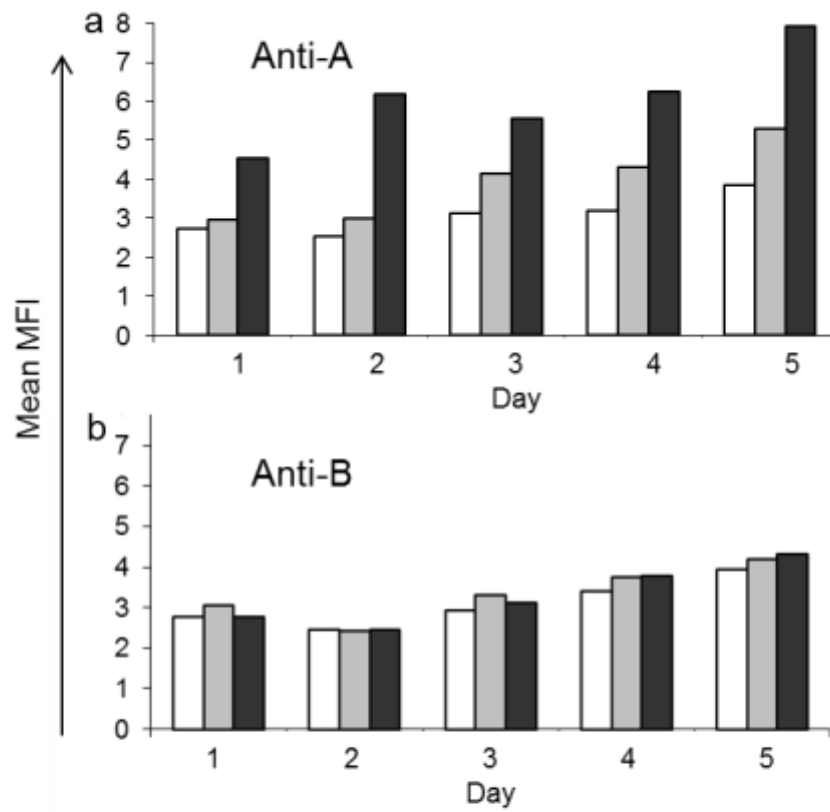


Figure 4.

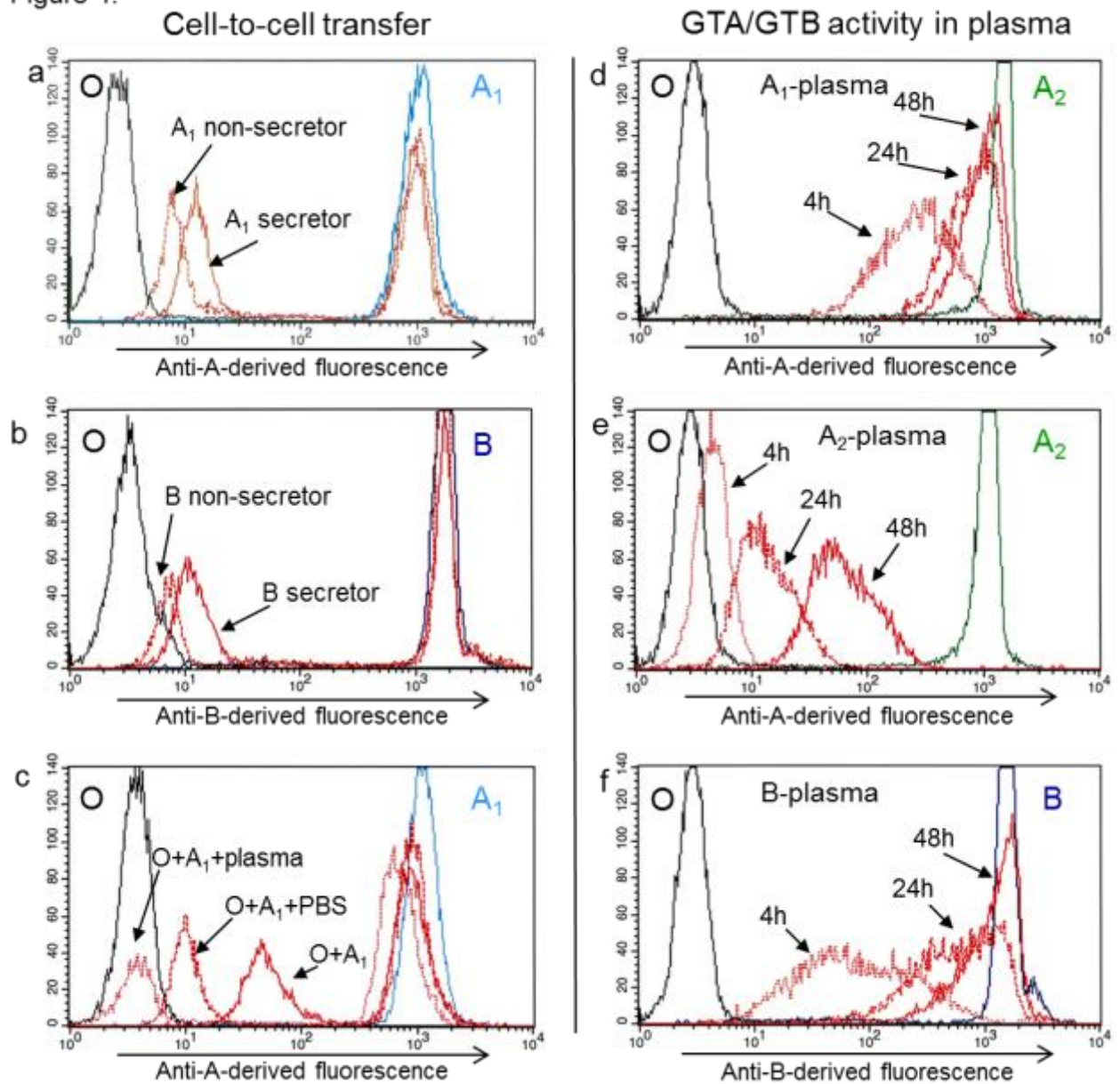


Figure legends

Fig. 1. Schematic overview of *in vitro* experiments.

Fig. 2. Flow cytometry testing of samples from recipients (Rec) of either HSCs or blood transfusions of blood group O. Histograms from flow cytometric testing of RBC samples. Colour code: red lines represent the patients' samples. Control RBC are included in each run. The x axis represent PE-derived fluorescence on a logarithmic scale while the y axis shows the number of cells on a linear scale.

(a) Post-transplant testing with anti-A of an A secretor patient who had received HSC from a group O donor. An almost A_x-like antigen level was detected on the donor-derived group O RBC. (b) Post-transplant testing with anti-A of an A non-secretor patient who had received HSC from a group O donor. Weak expression of A antigen was detected on the donor-derived group O RBC. (c and d) Post-transplant testing with anti-A and anti-B, respectively, of an AB secretor patient who had received HSC from a group O donor. Weak expression of A antigen on the donor-derived group O RBC was detected with anti-A but no B antigen could be detected with anti-B. (e) Two secretor patients, originally defined as A^2O^{lv} (solid red line) and A^1O^2 (dashed red line), respectively, with similar transplantation/transfusion histories but differing levels of detectable A antigen on the donor-derived group O RBC. (f) Post-transfusion testing with anti-A of an A secretor patient who had received blood transfusions from group O donors. (g) Post-transfusion testing with anti-A of an A non-secretor patient who had received blood transfusions from group O donors. (h) Post-transfusion testing with anti-A of an A secretor patient who had received blood transfusions from group O donors. Three populations of cells are seen, one expressing A antigen at a normal level and two populations of donor-derived O RBC

expressing no or low levels of A antigen. The patient had been transfused just prior to sampling.

Fig. 3. Flow cytometric testing of cell-plasma mixes. Two different group O RBC were incubated in parallel with either group O (□), A₁ or B non-secretor (▣) or A₁ or B secretor (■) plasma. Changes in mean MFI of the group O RBC are shown over time. (a) O RBC mixed with either O, A₁ secretor or A₁ non-secretor plasma incubated at 37°C and tested with anti-A. The rise in MFI is clearly seen for the O RBC/ A₁ secretor plasma mix. (b) O RBC mixed with either O, B secretor or B non-secretor plasma incubated at 37°C and tested with anti-B. There was no obvious rise in MFI in comparison to the O plasma control.

Fig. 4. *In vitro* experiments to examine cell-to-cell transfer of A/B antigens (a-c) and detection of GTA/GTB activity in plasma (d-f). Control RBCs are included in the flow cytometry testing and were run in parallel with the samples of interest. In the histograms the x axis represent PE-derived fluorescence on a logarithmic scale while the y axis shows the number of cells on a linear scale.

The cell-cell mixes were incubated at 37° for 24 h under constant mixing and subsequently tested with anti-A or anti-B. (a) Group O RBCs mixed with either A₁ secretor (solid red line) or A₁ non-secretor (dashed red line) RBCs. Clearly detectable levels of A antigen are seen on the RBCs originally typed as group O. A slightly higher expression is seen for O RBCs incubated with A₁ secretor RBCs in comparison to A₁ non-secretor RBCs. (b) Group O RBC mixed with either B secretor (solid red line) or B non-secretor (dashed red line) RBC and tested with anti-B. Clearly detectable levels of B antigen are seen on the RBCs originally typed as group O. A slightly higher expression is seen for O RBCs

incubated with B secretor RBCs in comparison to B non-secretor RBCs. (c) Flow cytometric testing of cell-cell mixes and with either PBS or A non-secretor plasma added. Different levels of A antigen were detected with anti-A in the different mixes. (d-f) Histograms from flow cytometric testing of RBC/plasma mixes with added substrate. Control RBCs are included in each run. All mixes show a rise in MFI over time. (d) O RBCs incubated with A₁ plasma, UDP-GalNAc and MnCl₂, tested with anti-A. (e) O RBCs incubated with A₂ plasma, UDP-GalNAc and MnCl₂, tested with anti-A. (f) O RBCs incubated with B plasma UDP-Gal and MnCl₂, tested with anti-B.