Biomacromolecules

pubs.acs.org/Biomac

Article

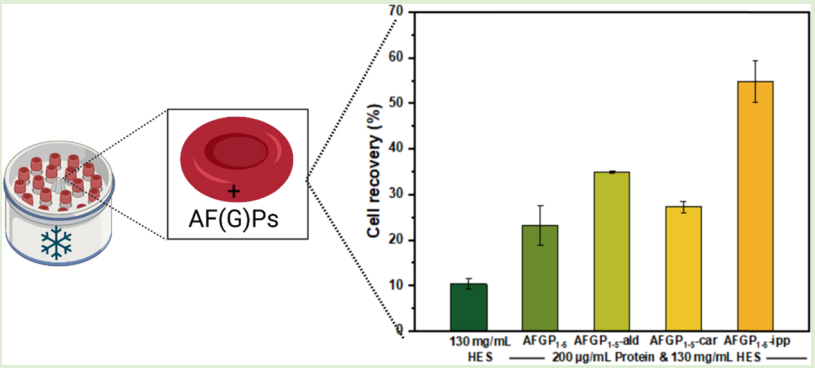
Ice Recrystallization Inhibition Is Insufficient to Explain Cryopreservation Abilities of Antifreeze Proteins

Yuling Sun, Daria Maltseva, Jie Liu, Theordore Hooker, II, Volker Mailänder, Hans Ramløv, Arthur L. DeVries, Mischa Bonn, and Konrad Meister*

Cite This: *Biomacromolecules* 2022, 23, 1214–1220

Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information



ABSTRACT: Antifreeze proteins (AFPs) and glycoproteins (AFGPs) are exemplary at modifying ice crystal growth and at inhibiting ice recrystallization (IRI) in frozen solutions. These properties make them highly attractive for cold storage and cryopreservation applications of biological tissue, food, and other water-based materials. The specific requirements for optimal cryostorage remain unknown, but high IRI activity has been proposed to be crucial. Here, we show that high IRI activity alone is insufficient to explain the beneficial effects of AF(G)Ps on human red blood cell (hRBC) survival. We show that AF(G)Ps with different IRI activities cause similar cell recoveries of hRBCs and that a modified AFGP variant with decreased IRI activity shows increased cell recovery. The AFGP variant was found to have enhanced interactions with a hRBC model membrane, indicating that the capability to stabilize cell membranes is another important factor for increasing the survival of cells after cryostorage. This information should be considered when designing novel synthetic cryoprotectants.

INTRODUCTION

The transfusion of human red blood cells (hRBCs) is oftentimes the only option for patients suffering from leukemia, anemias, or traumas with severe blood loss.[1,2] Long-term storage of RBCs is further crucial for the storage of rare blood cells, military transfusions, or special autotransfusion programs.[3] Cryopreservation still remains the only method that allows long-term storage of hRBCs and access to quantities of hRBC units that are necessary when large numbers of hRBC transfusions are required.[4] Unwanted ice formation and recrystallization during thawing present major challenges for cryopreserved biological samples and cause cellular damage of tissues and hRBC apoptosis.[5,6] The clinical strategies for cryopreservation require the addition of high concentrations of cell-permeating cryoprotectants such as water-miscible organic solvents (e.g., glycerol and dimethyl sulfoxide).[7−9] However, the high concentration of cryoprotectants and the toxicity of solvents require time-consuming removal of traces of toxic solvents, conflicting with rapid transplant or transfusions. Furthermore, the current cryopreservation protocols do not effectively control extracellular ice growth, leaving tissues vulnerable to cellular damage.[7,10,11] Organisms inhabiting freezing environments and prone to ice recrystallization (IRI) injuries have evolved biomolecular solutions to enable life to flourish under icy conditions.[12−14] They produce antifreeze proteins (AFPs) and glycoproteins (AFGPs) that have the ability to inhibit IRI,[15] the ability to shape ice crystals into unusual morphologies,[16] and the ability to depress the freezing point in a noncolligative manner (thermal hysteresis, TH).[17] The relative magnitude of each effect varies between individual AF(G)Ps, with the AFGPs being the by far most potent IRI inhibitors.[16,18] High IRI activity has been suggested to be key for optimal

Received: November 11, 2021
Revised: January 11, 2022
Published: January 26, 2022

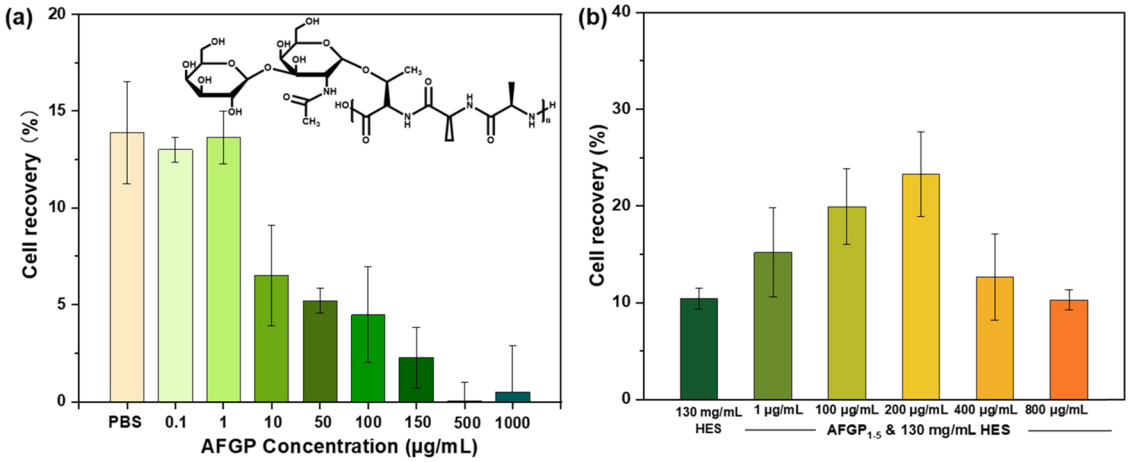


Figure 1. Cryopreservation of hRBC in the presence of $AFGP_{1-5}$. (a) Recovery of hRBC cryopreserved in PBS solutions with different concentrations of $AFGP_{1-5}$ thawed at 45 °C. (b) Recovery of hRBC cryopreserved in HES solutions (130 mg/mL) with different $AFGP_{1-5}$ concentrations thawed at 23 °C. Experiments were performed three times, and the error bars represent the standard deviation between the individual measurements.

cryopreservation effects, and substantial efforts have been made to develop synthetic compounds that mimic AF(*G*)Ps IRI properties to increase cellular survival.[5,10,19,20] However, up to now, the most active synthetic IRI compounds are substantially less active than their natural counterparts, and antifreeze mimics are rarely used in real-life applications. Recently, numerous studies have reported hydroxyethyl starch (HES) as a promising nonvitrifying cryoprotectant of RBCs,[21,22] peripheral blood stem cells,[23,24] keratinocytes,[25−27] fibroblast,[26] and other cell types.[28,29] When used at appropriate concentrations, HES appears free of side effects and is less toxic than the commonly used cryoprotectants.[30−32] However, transfusions containing a high concentration of HES can also have unwanted side effects like the inhibition of hemostasis in vulnerable patients.[33,34]

The usage of AF(*G*)Ps to protect RBCs has been shown to reduce the destruction of RBCs, hemolysis, after cryopreservation.[35] Carpenter et al. showed that upon the addition of AFP I to RBCs cryopreserved in HES, their recovery due to the inhibition of IRI was enhanced.[11] Interestingly, it was further reported that AFPs type I, II, and III reduced hemolysis at micromolar concentrations while enhancing hemolysis at AFP millimolar concentrations.[36] The origin of this discrepancy, the specific requirements for optimized cryopreservation of AF(*G*)Ps and mimics, and the role of IRI activity in cryopreservation remain debated. Here, we investigate the effects of different AF(*G*)Ps and variants on the survival of hRBC after cryostorage. Our results reveal that IRI activity alone is insufficient to explain the cell recovery after cryopreservation and that favorable protein-membrane interactions seem important.

MATERIALS AND METHODS

Human RBCs Preparation. Human blood was collected from healthy donors and centrifuged (1940*g*, 5 min, 25 °C). The top layer (buffy coat and plasma) was removed and replaced with an equal volume of PBS buffer (Dulbecco's phosphate-buffered saline, 1×, without calcium and magnesium). The RBCs were then washed three times with PBS buffer using identical conditions. The final PBS solution of RBCs had a packed cell volume of ∼40%. Human blood was obtained from the Department of Transfusion Medicine Mainz from 10 healthy donors after physical examination and after obtaining their informed consent in accordance with the Declaration of Helsinki. The use of human blood was approved by the local ethics committee "Landesärztekammer Rheinland-Pfalz" (837.439.12 (8540-F)).

$AFGP_{1-5}$ was purified from the Antarctic toothfish *Dissostichus mawsoni*, as described previously.[28] The $AFGP_{1-5}$ variants were made by established protocols, as described recently.[37] AFP I was purified from winter flounder, *Pseudopleuronectes americanus*. RmAFP was obtained by recombinant protein expression, as described elsewhere. Quaternary aminoethyl (QAE) (AFP-III) was purified from the Antarctic eelpout (*Lycodichthys dearborni*) or obtained by recombinant protein expression, including the mutant T18N. In this mutant, the threonine residue at position 18 is replaced by asparagine, which causes the complete loss of antifreeze activity.

Cryopreservation of RBCs. Freshly prepared human RBCs (50 μL) (packed cell volume ∼40%) were added to 50 μL of cryoprotectant ($AFGP_{1-5}$, AF(*G*)Ps/HES, or AF(*G*)Ps variants/HES) in cryovials and was gently mixed using a vortex. Triplicate independent samples were characterized for each group. All samples were rapidly frozen in liquid nitrogen and stored in liquid nitrogen for 20 min. Samples were thawed for 10 min in a 45 °C water bath or for 20 min at room temperature (22 ± 1 °C).

Control samples (0% hemolysis) were prepared by adding 50 μL of freshly prepared hRBC to PBS buffer and storing them for 1 h at room temperature. Control samples (100% hemolysis) were prepared by adding 50 μL of freshly prepared hRBC to 50 μL of milli-Q water, and samples were vortexed. The 100% hemolysis samples were rapidly frozen in liquid nitrogen and stored in liquid nitrogen for 20 min. Samples were thawed for 10 min in a 45 °C water bath or for 20 min at room temperature (23 ± 1 °C).

Measurement of RBC Hemolysis and Cell Recovery. Sixty microliters of RBC/cryoprotectant suspension were added into 540 μL of PBS solution and centrifuged (500*g*, 5 min, 4 °C). Thereafter, 200 μL of the supernatant was removed and added into 3.8 mL of PBS solution. Absorbance was measured with an ultraviolet/visible (UV/vis) spectrometer (Lambda 900, Perkin Elmer) at 414 nm (1 cm light path). Hemolysis (%) and cell recovery (%) were calculated according to eqs 1 and 2, respectively. Triplicate samples were characterized for each group.

$$\text{Hemolysis (\%)} = \frac{\text{Abs} - \text{Abs (0\%hemolysis)}}{\text{Abs (100\%hemolysis)} - \text{Abs (0\%hemolysis)}} *100 \quad (1)$$

$$\text{Cell recovery (\%)} = 100\ (\%) - \text{hemolysis (\%)} \quad (2)$$

https://doi.org/10.1021/acs.biomac.1c01477
Biomacromolecules 2022, 23, 1214−1220

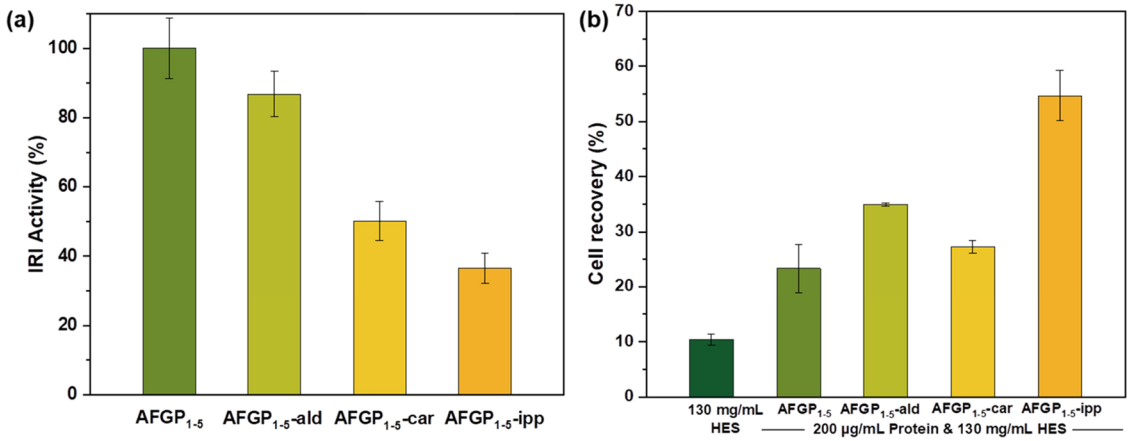


Figure 2. (a) IRI inhibition activity of $AFGP_{1-5}$ and the different variants. The IRI activity of $AFGP_{1-5}$-ald, $AFGP_{1-5}$-car, and $AFGP_{1-5}$-ipp at 2 μg/mL is reduced by ~13, 50, and 63%, respectively. Reprinted with permission from ref 37. Copyright 2021 ACS Publications.[37] (b) Effects of $AFGP_{1-5}$ and different variants on the cell recovery of cryopreserved hRBCs in HES solution (130 mg/mL), thawed at 23 °C. Experiments were performed three times, and the error bars represent the standard deviation between the individual measurements.

The Abs (0% hemolysis) and Abs (100% hemolysis) represent the 414 nm absorbance values of the 0% and 100% hemolysis and control samples.

Preparation of the RBC Model Membrane. The phospholipids 1,2-dioleoyl-sn-glycero-3-phosphocholine (DOPC), N-palmitoyl-D-erythro sphingosylphosphorylcholine (SM), and 1,2-dioleoyl-sn-glycero-3-phosphoethanolamine (DOPE) (Avanti Polar Lipids) were dissolved in chloroform/methanol (9:1 mixture (vol/vol)) at a ratio of 45:45:10 (mol %). This composition was reported to serve as a phospholipid model of the outer leaflet of human RBC membranes.[38]

Surface Pressure Measurements. Surface pressure measurements were performed in a custom-made Teflon trough filled with 5 mL of PBS buffer at room temperature (22 ± 1 °C) using a DeltaPi tensiometer (KBN 315 Sensor Head, Kibron Inc.). The surface pressure experiments were also performed under a nitrogen atmosphere to prevent the oxidation of unsaturated lipids.[39,40] Surface pressure measurements were first performed at the air/buffer interface, and the phospholipid mixture solution of DOPC/SM/DOPE was spread droplet by droplet at the air/ buffer interface using a Hamilton syringe.[41,42] $AFGP_{1-5}$ (200 μL), $AFGP_{1-5}$-ipp (5 mg/mL in PBS), or pure buffer was injected into the subphase. The bulk AFGP concentration was 0.2 mg/mL.

RESULTS

The cryopreservation of hRBCs was evaluated using a rapid freezing protocol, following experimental procedures described in established protocols.[7,10] Samples were rapidly frozen by immersion in liquid nitrogen and subsequently stored at −196 °C. Cell recoveries were determined after thawing at an ambient temperature of 23 °C or at 45 °C.

Figure 1a shows the results of the hRBC cryopreservation experiment in PBS buffer. The cell survival of hRBCs in PBS buffer was found to be low, with a recovery of ~14%. Upon the addition of $AFGP_{1-5}$, the cell recovery decreased with increasing $AFGP_{1-5}$ concentration. We found that for $AFGP_{1-5}$ concentrations exceeding 150 μg/mL, the hRBC cell recovery was only ~2%. Clearly, the presence of $AFGP_{1-5}$ in PBS buffer caused more damage than protection to the hRBC. This finding is in line with the results from previous RBC cryopreservation studies using AFP type I and III.[11,36] AFGPs can bind to ice crystals[43] and shape small ice crystals to blunt hexagonal bipyramid crystals at a temperature slightly below its melting point. Upon lowering the temperature below the hysteresis gap, an ice crystal in the presence of AFGPs will rapidly grow into a bundle of spicular ice needles that likely damage the cells.[44] During the rapid freezing and thawing process, which mimics the cryopreservation of RBCs, bipyramidal,[11] needle-like, and specular ice crystals[45] were observed in the presence of AFPs, which damaged the RBCs and reduced cell survival significantly. Upon increasing the $AFGP_{1-5}$ concentrations in PBS buffer, this effect will become increasingly prominent, likely leading to the observed lower cell recovery of hRBCs.

Next, we investigated the capacity of $AFGP_{1-5}$ to increase the survival of hRBC in HES solutions. We find that low (130 mg/mL) and high (215 mg/mL) concentrations of HES resulted in ~12 and ~78% hRBC recovery (Figures 1b and S1), respectively, and these cell recoveries are consistent with previous studies.[10] Compared with $AFGP_{1-5}$ in PBS buffer, which caused significant damage to hRBCs, $AFGP_{1-5}$ in HES solution exhibits much better protection owing to the suppression of the explosive ice growth beyond the TH gap.[44] Even higher cell recovery rates can be obtained for $AFGP_{1-5}$ in high HES concentrations (215 mg/mL), but the very high HES concentration also leads to very viscous solutions with high osmotic pressure, which is impractical for clinical cryopreservation.[44,46] In addition, transfusions containing high concentrations of HES have been shown to cause unwanted side effects like the inhibition of hemostasis in vulnerable patients.[33] Therefore, the ability of AFGPs to modulate cellular recovery at low HES concentrations (130 mg/mL) will be investigated.

Figure 1b shows the results of the cryopreservation experiment of $AFGP_{1-5}$ in a 130 mg/mL HES solution. The effect of $AFGP_{1-5}$ on the hRBC cryopreservation survival was again dependent on the $AFGP_{1-5}$ concentration. We find that the cell recovery of hRBCs increased for concentrations up to 200 μg/mL $AFGP_{1-5}$ but decreased again at higher concentrations. The addition of 200 μg/mL $AFGP_{1-5}$ showed the highest cell recovery (~24%) with twice the cell recovery of 130 mg/mL HES alone. The subsequent decrease in the cell recovery at higher concentrations agrees with observations for PVA,[10] AFGP analogs,[47] and AFP I.[11]

In order to determine whether there is a correlation between IRI activity and cryopreservation efficacy, three $AFGP_{1-5}$ variants with different IRI and TH activities were investigated.

https://doi.org/10.1021/acs.biomac.1c01477
Biomacromolecules 2022, 23, 1214−1220

In these variants, the hydroxyl groups of the galactose moieties of the natural $AFGP_{1-5}$ isoforms were modified into $AFGP_{1-5}$-aldehyde ($AFGP_{1-5}$-ald), $AFGP_{1-5}$-carboxyl ($AFGP_{1-5}$-car), and $AFGP_{1-5}$-isopropylidene ($AFGP_{1-5}$-ipp), as described recently.[37,48] Because of the modifications, the IRI activities of $AFGP_{1-5}$-ald, $AFGP_{1-5}$-car, and $AFGP_{1-5}$-ipp were reduced by 13, 50, and 63%, respectively, relative to native $AFGP_{1-5}$ (Figure 2a).[37]

We investigated the cryopreservation abilities of the variants at 200 μg/mL concentrations in HES (130 mg/mL) because these conditions showed the maximum cryopreservation efficiency for the native $AFGP_{1-5}$. The results are shown in Figure 2b. Despite having lower IRI activity, the hRBC recovery of all three variants was increased. The cell recovery of $AFGP_{1-5}$-ald and $AFGP_{1-5}$-car was increased from 24% for $AFGP_{1-5}$ to 35 and 27%, while $AFGP_{1-5}$-ipp more than doubled cell recovery to 55%. Thus, despite having the lowest IRI activity (37% of native $AFGP_{1-5}$), the $AFGP_{1-5}$-ipp variant enabled the highest hRBC recovery, more than double that of native $AFGP_{1-5}$.

Next, we determined the effects of five additional AF(*G*)Ps with varying IRI activities[18] and compared their ability to improve the survival of hRBCs that were cryopreserved in 130 mg/mL HES solutions (Figure 3). $AFGP_{7-8}$ is an isoform and

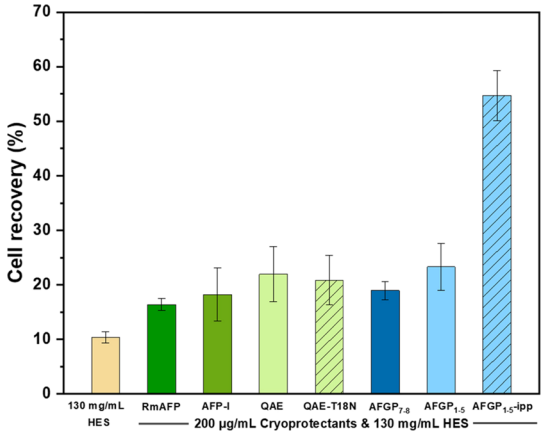


Figure 3. Effect of different AF(*G*)Ps and variants on the cell recovery of cryopreserved hRBC in HES solution (130 mg/mL), thawed at 23 °C. Experiments were performed three times, and the error bars represent the standard deviation between the individual measurements.

low-molecular-weight variant of the AFGPs and possesses only ~60% of the antifreeze activity of the larger $AFGP_{1-5}$.[43,49] *Rm*AFP is derived from the beetle *Rhagium mordax* and is considered to be a hyperactive AFP.[14] QAE is a version of AFP type III with QAE-sephadex-binding,[43,49] and AFP type I is a moderate AFP derived from winter flounder *Pseudopleuronectes americanus*. For the QAE mutant (QAE-T18N), the threonine 18 residue in the center of the ice-binding site was replaced by asparagine, causing a complete loss of TH activity[50] and no effect on IRI activity.[51] We find that the different AF(*G*)Ps show remarkably similar cell recoveries (~20%) of hRBC despite displaying very different IRI activities (Figure S2). Interestingly, QAE-T18N has the same cell recovery as QAE, revealing that the T18N mutation and the associated loss of TH activity have little effect on the cryopreservation ability of hRBC. Of all investigated AF(*G*)Ps, the $AFGP_{1-5}$-ipp variant shows the highest cell recovery of cryopreserved hRBC. Apparently, the factors influencing the cryopreservation ability of an AF(*G*)P are more complex and not solely dependent on IRI activity.

We performed surface pressure experiments of erythrocyte model membranes to further investigate the reason for $AFGP_{1-5}$-ipp's superior cryoprotective properties. Figure 4 shows the effect of $AFGP_{1-5}$ and $AFGP_{1-5}$-ipp on a model membrane mimicking the erythrocyte outer membrane, consisting of the phospholipid mixture DOPC, SM, and DOPE (45:45:10 (mol %)).[38] The surface pressure of the model membrane in PBS buffer was set to ~24 mN/m, typical for a well-ordered, liquid-condensed model membrane.[52] When proteins were injected under the monolayer, they are allowed to interact with the monolayer. If part of the protein inserts itself in between the lipid molecules or in any way disturbs the lipid packing, the surface pressure will increase. The increase hence suggests that the protein can interact with the monolayer.[41] We find that the surface pressure increases substantially upon the addition of $AFGP_{1-5}$ and $AFGP_{1-5}$-ipp into the PBS subphase of the DOPC/SM/DOPE monolayer, as shown in Figure 4. This indicates that $AFGP_{1-5}$ and $AFGP_{1-5}$-ipp interact with the monolayer. $\Delta\pi$ represents the difference in the surface pressure after the addition of $AFGP_{1-5}$/$AFGP_{1-5}$-ipp and of the PBS buffer. The increase in surface pressure upon $AFGP_{1-5}$/$AFGP_{1-5}$-ipp injections suggests protein-membrane interactions and possible stabilization of the model membrane. We find the interaction of $AFGP_{1-5}$-ipp with the membrane to be stronger than that of $AFGP_{1-5}$, as indicated by the $\Delta\pi$ of $AFGP_{1-5}$-ipp, which is much higher than that for $AFGP_{1-5}$ (Figure 4a).

DISCUSSION

The cryopreservation of cells causes cold stress that affects the cell physiology, metabolic activity, and regulation of ion equilibration across membranes. The crystallization of water into ice is further detrimental to tissues, and the process of IRI upon thawing is the major contributor to cell death. We find that the addition of $AFGP_{1-5}$ to a HES cryostorage medium has a statistically significant positive effect on the survival of hRBCs, which is consistent with previous studies on nonglycosylated AFPs.[11,36] Different AFP classes with varying IRI activities showed very similar cell recovery of hRBC (~20%), suggesting that IRI activity alone is not sufficient to predict cell recovery after cryopreservation. Interestingly, the chemically modified $AFGP_{1-5}$-ipp variant with additional hydrophobic groups on the galactose moieties promoted cell recovery of hRBC to 55% compared to the 24% of AFGP, while having decreased IRI and TH activity. Apparently, high IRI activity alone is insufficient to explain the beneficial effects of AF(*G*)Ps on hRBC survival after cryopreservation. Alternative mechanisms that explain the positive effect of AF(*G*)Ps on the cold survival of cells involve the protection of cell membranes as they pass through their phase transition temperatures as well as the blockage or alteration of the flow of ions into cells. Tomczak et al. proposed that AF(*G*)Ps insert into membranes through hydrophobic interactions, thereby altering the molecular packing of the acyl chains, resulting in reduced membrane permeability and improved cryopreservation efficiency.[53] We find that increasing AFGP hydrophobicity by adding an isopropylidene group leads to improved hRBC survival and stronger interaction with an erythrocyte model membrane. We hypothesize that the stabilization of the RBC membranes through AFGP and via hydrophobic interactions is

https://doi.org/10.1021/acs.biomac.1c01477
Biomacromolecules 2022, 23, 1214−1220

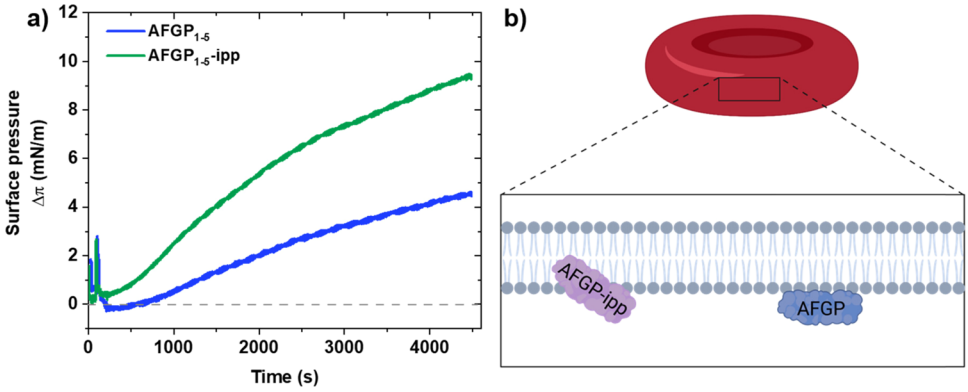


Figure 4. Interactions of $AFGP_{1-5}$ with erythrocyte model membranes. (a) Difference in surface pressure $\Delta\pi$ versus time after the addition of $AFGP_{1-5}$-ipp and $AFGP_{1-5}$ into the PBS subphase of the DOPC/SM/DOPE monolayer. $\Delta\pi$ represents the change in the surface pressure after the addition of $AFGP_{1-5}$ (5 mg/mL) and of PBS buffer. (b) Schematic representation of $AFGP_{1-5}$-ipp and $AFGP_{1-5}$ proteins interacting with an RBC model membrane.

enhanced, owing to the modification. This modification substantially increases hRBC recovery. We suggest that apart from IRI activity, the capabilities to stabilize cell membranes and the cellular location of the cryoprotectants are additional key components for the cell recovery of hRBC after cryopreservation. However, membrane stabilization is an important but not the sole determining factor for cell survival after cryostorage. For example, bovine serum albumin is a membrane stabilizing agent,[54] but it is usually used as a negative control for cryopreservation study.[55] Apart from proteins, the lipids, sugars, and amino acids also seem to exert their cryoprotective effect at least partly by stabilizing the plasma membrane.[54,56] Therefore, the combination of high IRI activity and capabilities to stabilize cell membranes is likely essential for optimizing cell survival after cryostorage.

CONCLUSIONS

Herein, we found a variety of antifreeze proteins that show similar cell recoveries of hRBCs despite having very different IRI activities. In addition, a chemically modified $AFGP_{1-5}$-ipp variant with additional hydrophobic groups on the galactose moiety has decreased IRI activity but showed significantly increased cell recovery compared to $AFGP_{1-5}$. Surface pressure experiments with the $AFGP_{1-5}$-ipp variant showed enhanced interactions with RBC model membranes, indicating that membrane stabilization is another key factor in the survival of cells after cryostorage. We conclude that high IRI activity alone is insufficient to explain the beneficial effects of AF(*G*)Ps hRBC survival. The ability to stabilize cell membranes and the cellular location of the cryoprotectants are also likely crucial for cryopreservation and should be considered for the design of novel synthetic cryoprotectants.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.biomac.1c01477.

Influence of different AF(*G*)Ps on the cryopreservation of hRBC; IRI efficacy of various AF(*G*)Ps and their variants (PDF)

AUTHOR INFORMATION

Corresponding Author

Konrad Meister − *Max Planck Institute for Polymer Research, 55128 Mainz, Germany; University of Alaska Southeast, Juneau, Alaska 99801, United States;* orcid.org/0000-0002-6853-6325; Email: meisterk@mpip-mainz.mpg.de

Authors

Yuling Sun − *Max Planck Institute for Polymer Research, 55128 Mainz, Germany; Institute of Chemistry, Chinese Academy of Sciences, Beijing 100190, P. R. China;* orcid.org/0000-0001-8582-5244

Daria Maltseva − *Max Planck Institute for Polymer Research, 55128 Mainz, Germany*

Jie Liu − *Institute of Chemistry, Chinese Academy of Sciences, Beijing 100190, P. R. China*

Theordore Hooker, II − *University of Alaska Southeast, Juneau, Alaska 99801, United States*

Volker Mailänder − *Max Planck Institute for Polymer Research, 55128 Mainz, Germany; Dermatology Department, University Medical Center of the Johannes Gutenberg-University, 55131 Mainz, Germany*

Hans Ramløv − *Roskilde University, 4000 Roskilde, Denmark;* orcid.org/0000-0003-1113-0583

Arthur L. DeVries − *University of Illinois at Urbana−Champaign, Urbana, Illinois 61801, United States*

Mischa Bonn − *Max Planck Institute for Polymer Research, 55128 Mainz, Germany;* orcid.org/0000-0001-6851-8453

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.biomac.1c01477

Funding

Open access funded by Max Planck Society.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

K. Meister acknowledged support from BlaST, which is supported by the NIH Common Fund, through the Office of Strategic Coordination, Office of the NIH Director with the linked awards: TL4GM118992, RL5GM118990, and UL1GM118991. Research reported in this publication was also supported by an Institutional Development Award (IDeA)

from the National Institute of General Medical Sciences of the National Institutes of Health under Grant No. 2P20GM103395. The content is solely the responsibility of the authors and does not necessarily represent the official view of the National Institutes of Health. Y.S. acknowledges support from the International Postdoctoral Exchange Fellowship Program of China. Figure 4 and the TOC were created using BioRender.com.

■ ABBREVIATIONS

AFPs, antifreeze proteins; AFGPs, antifreeze glycoproteins; AF(G)Ps, antifreeze proteins and glycoproteins; hRBC, human red blood cell; TH, thermal hysteresis; IRI, ice recrystallization inhibition; $AFGP_{1-5}$-ipp, $AFGP_{1-5}$-isopropylidene; $AFGP_{1-5}$-ald, $AFGP_{1-5}$-aldehyde; $AFGP_{1-5}$-car, $AFGP_{1-5}$-carboxyl; PBS, phosphate-buffered saline buffer; HES, hydroxyethyl starch; DOPE, 1,2-dioleoyl-sn-glycero-3-phosphoethanolamine; DOPC, 1,2-dioleoyl-sn-glycero-3-phosphocholine; SM, N-palmitoyl-D-erythrosphingosylphosphorylcho-line

■ REFERENCES

(1) García-Roa, M.; del Carmen Vicente-Ayuso, M.; Bobes, A. M.; Pedraza, A. C.; González-Fernández, A.; Martín, M. P.; Sáez, I.; Seghatchian, J.; Gutiérrez, L. Red Blood Cell Storage Time and Transfusion: Current Practice, Concerns and Future Perspectives. *Blood Transfus.* **2017**, *15*, 222.

(2) Napolitano, L. M.; Kurek, S.; Luchette, F. A.; Anderson, G. L.; Bard, M. R.; Bromberg, W.; Chiu, W. C.; Cipolle, M. D.; Clancy, K. D.; Diebel, L. Clinical Practice Guideline: Red Blood Cell Transfusion in Adult Trauma and Critical Care. *J. Trauma Acute Care Surg.* **2009**, *67*, 1439−1442.

(3) Bohoněk, M., Cryopreservation of Blood. *Blood transfusion in clinical practice*; InTech Open, 2012; pp 233−242.

(4) Scott, K. L.; Lecak, J.; Acker, J. P. J. T. Biopreservation of Red Blood Cells: Past, Present, and Future. *Transfus. Med. Rev.* **2005**, *19*, 127−142.

(5) Wang, Z.; Yang, B.; Chen, Z.; Liu, D.; Jing, L.; Gao, C.; Li, J.; He, Z.; Wang, J. Bioinspired Cryoprotectants of Glucose-Based Carbon Dots. *ACS Appl. Bio Mater.* **2020**, *3*, 3785−3791.

(6) Xue, B.; Zhao, L.; Qin, X.; Qin, M.; Lai, J.; Huang, W.; Lei, H.; Wang, J.; Wang, W.; Li, Y. Bioinspired Ice Growth Inhibitors Based on Self-Assembling Peptides. *ACS Macro Lett.* **2019**, *8*, 1383−1390.

(7) Bai, G.; Song, Z.; Geng, H.; Gao, D.; Liu, K.; Wu, S.; Rao, W.; Guo, L.; Wang, J. Oxidized Quasi-Carbon Nitride Quantum Dots Inhibit Ice Growth. *Adv. Mater.* **2017**, *29*, No. 1606843.

(8) Deller, R. C.; Vatish, M.; Mitchell, D. A.; Gibson, M. I. Glycerol-Free Cryopreservation of Red Blood Cells Enabled by Ice-Recrystallization-Inhibiting Polymers. *ACS Biomater. Sci. Eng.* **2015**, *1*, 789−794.

(9) Lagerberg, J. W. Cryopreservation of Red Blood Cells. *Methods Mol. Biol.* **2015**, *1257*, 353−367.

(10) Deller, R. C.; Vatish, M.; Mitchell, D. A.; Gibson, M. I. J. N. Synthetic Polymers Enable Non-Vitreous Cellular Cryopreservation by Reducing Ice Crystal Growth During Thawing. *Nat. Commun.* **2014**, *5*, 3244.

(11) Carpenter, J. F.; Hansen, T. N. Antifreeze Protein Modulates Cell Survival During Cryopreservation: Mediation through Influence on Ice Crystal Growth. *Proc. Natl. Acad. Sci. U. S. A.* **1992**, *89*, 8953−8957.

(12) Meister, K.; Ebbinghaus, S.; Xu, Y.; Duman, J. G.; DeVries, A.; Gruebele, M.; Leitner, D. M.; Havenith, M. J. P. Long-Range Protein−Water Dynamics in Hyperactive Insect Antifreeze Proteins. *Proc. Natl. Acad. Sci. U. S. A.* **2013**, *110*, 1617−1622.

(13) DeVries, A. L.; Wohlschlag, D. E. Freezing Resistance in Some Antarctic Fishes. *Science* **1969**, *163*, 1073−1075.

(14) Meister, K.; Moll, C.; Chakraborty, S.; Jana, B.; DeVries, A.; Ramløv, H.; Bakker, H. Molecular Structure of a Hyperactive Antifreeze Protein Adsorbed to Ice. *J. Chem. Phys.* **2019**, *150*, 131101.

(15) Knight, C. A.; De Vries, A. L.; Oolman, L. D. Fish Antifreeze Protein and the Freezing and Recrystallization of Ice. *Nature* **1984**, *308*, 295−296.

(16) Budke, C.; Dreyer, A.; Jaeger, J.; Gimpel, K.; Berkemeier, T.; Bonin, A. S.; Nagel, L.; Plattner, C.; DeVries, A. L.; Sewald, N.; Koop, T. Quantitative Efficacy Classification of Ice Recrystallization Inhibition Agents. *Cryst. Growth Des.* **2014**, *14*, 4285−4294.

(17) Kristiansen, E.; Zachariassen, K. E. The Mechanism by Which Fish Antifreeze Proteins Cause Thermal Hysteresis. *Cryobiology* **2005**, *51*, 262−280.

(18) Olijve, L. L. C.; Meister, K.; Devries, A. L.; Duman, J. G.; Guo, S.; Bakker, H. J.; Voets, I. K. Blocking Rapid Ice Crystal Growth through Nonbasal Plane Adsorption of Antifreeze Proteins. *Proc. Natl. Acad. Sci. U. S. A.* **2016**, *113*, 3740−3745.

(19) Geng, H.; Liu, X.; Shi, G.; Bai, G.; Ma, J.; Chen, J.; Wu, Z.; Song, Y.; Fang, H.; Wang, J. Graphene Oxide Restricts Growth and Recrystallization of Ice Crystals. *Angew Chem., Int. Ed. Engl.* **2017**, *56*, 997−1001.

(20) Zhu, W.; Guo, J.; Agola, J. O.; Croissant, J. G.; Wang, Z.; Shang, J.; Coker, E. N.; Motevalli, B.; Zimpel, A.; Wuttke, S. Metal-Organic Framework Nanoparticle-Assisted Cryopreservation of Red Blood Cells. *J. Am. Chem. Soc.* **2019**, *141*, 7789−7796.

(21) Allen, E. D.; Weatherbee, L.; Spencer, H.; Lindenauer, S. M.; Permoad, P. Large Unit Red Cell Cryopreservation with Hydroxyethyl Starch. *Cryobiology* **1976**, *13*, 500−506.

(22) Lionetti, F. J.; Hunt, S. M. Cryopreservation of Human Red Cells in Liquid Nitrogen with Hydroxyethyl Starch. *Cryobiology* **1975**, *12*, 110−118.

(23) Stiff, P. J.; Murgo, A. J.; Zaroulis, C. G.; DeRisi, M. F.; Clarkson, B. D. Unfractionated Human Marrow Cell Cryopreservation Using Dimethylsulfoxide and Hydroxyethyl Starch. *Cryobiology* **1983**, *20*, 17−24.

(24) Lapisson, G.; Salinas, C.; Malacher, P.; Michallet, M.; Philip, I.; Philip, T. Cryopreservation with Hydroxyethylstarch (Hes)+ Dimethylsulfoxide (Dmso) Gives Better Results Than Dmso Alone. *Bull. Cancer* **2004**, *91*, 10097−10102.

(25) Pasch, J.; Schiefer, A.; Heschel, I.; Rau, G. Cryopreservation of Keratinocytes in a Monolayer. *Cryobiology* **1999**, *39*, 158−168.

(26) Naaldijk, Y.; Johnson, A. A.; Friedrich-Stockigt, A.; Stolzing, A. Cryopreservation of Dermal Fibroblasts and Keratinocytes in Hydroxyethyl Starch-Based Cryoprotectants. *BMC Biotechnol.* **2016**, *16*, 85.

(27) Pasch, J.; Schiefer, A.; Heschel, I.; Dimoudis, N.; Rau, G. Variation of the Hes Concentration for the Cryopreservation of Keratinocytes in Suspensions and in Monolayers. *Cryobiology* **2000**, *41*, 89−96.

(28) Ashwood-Smith, M.; Warby, C.; Connor, K.; Becker, G. Low-Temperature Preservation of Mammalian Cells in Tissue Culture with Polyvinylpyrrolidone (Pvp), Dextrans, and Hydroxyethyl Starch (Hes). *Cryobiology* **1972**, *9*, 441−449.

(29) Lionetti, F. J.; Hunt, S. M.; Gore, J. M.; Curby, W. A. Cryopreservation of Human Granulocytes. *Cryobiology* **1975**, *12*, 181−191.

(30) Waters, L.; Christensen, M.; Sato, R. Hetastarch: An Alternative Colloid in Burn Shock Management. *J. Burn Care Rehabil.* **1989**, *10*, 11−16.

(31) Stolzing, A.; Naaldijk, Y.; Fedorova, V.; Sethe, S. Hydroxyethylstarch in Cryopreservation−Mechanisms, Benefits and Problems. *Transfus. Apher. Sci.* **2012**, *46*, 137−147.

(32) Schmand, J. F.; Ayala, A.; Morrison, M. H.; Chaudry, I. H. Effects of Hydroxyethyl Starch after Trauma-Hemorrhagic Shock: Restoration of Macrophage Integrity and Prevention of Increased Circulating Interleukin-6 Levels. *Crit. Care Med.* **1995**, *23*, 806−814.

(33) Treib, J.; Baron, J.-F.; Grauer, M.; Strauss, R. An International View of Hydroxyethyl Starches. *Intensive Care Med.* **1999**, *25*, 258−268.

https://doi.org/10.1021/acs.biomac.1c01477
Biomacromolecules 2022, 23, 1214−1220

(34) Schramko, A. A.; Suojaranta-Ylinen, R. T.; Kuitunen, A. H.; Kukkonen, S. I.; Niemi, T. T. Rapidly Degradable Hydroxyethyl Starch Solutions Impair Blood Coagulation after Cardiac Surgery: A Prospective Randomized Trial. *Anesth. Analg.* **2009**, *108*, 30−36.
(35) Rubinsky, B.; Arav, A.; Devries, A. J. C. The Cryoprotective Effect of Antifreeze Glycopeptides from Antarctic Fishes. *Cryobiology* **1992**, *29*, 69−79.
(36) Chao, H.; Davies, P. L.; Carpenter, J. F. Effects of Antifreeze Proteins on Red Blood Cell Survival During Cryopreservation. *Eur. J. Exp. Biol.* **1996**, *199*, 2071−2076.
(37) Sun, Y.; Giubertoni, G.; Bakker, H. J.; Liu, J.; Wagner, M.; Ng, D. Y.; Devries, A. L.; Meister, K. Disaccharide Residues Are Required for Native Antifreeze Glycoprotein Activity. *Biomacromolecules* **2021**, *22*, 2595−2603.
(38) Virtanen, J. A.; Cheng, K. H.; Somerharju, P. Phospholipid Composition of the Mammalian Red Cell Membrane Can Be Rationalized by a Superlattice Model. *Proc. Natl. Acad. Sci. U. S. A.* **1998**, *95*, 4964−4969.
(39) Liljeblad, J. F.; Bulone, V.; Tyrode, E.; Rutland, M. W.; Johnson, C. M. Phospholipid Monolayers Probed by Vibrational Sum Frequency Spectroscopy: Instability of Unsaturated Phospholipids. *Biophys. J.* **2010**, *98*, L50−L52.
(40) Inoue, K.-i.; Takada, C.; Wang, L.; Morita, A.; Ye, S. In Situ Monitoring of the Unsaturated Phospholipid Monolayer Oxidation in Ambient Air by Hd-Sfg Spectroscopy. *J. Phys. Chem. B* **2020**, *124*, 5246−5250.
(41) Brockman, H. Lipid Monolayers: Why Use Half a Membrane to Characterize Protein-Membrane Interactions? *Curr. Opin. Struct. Biol.* **1999**, *9*, 438−443.
(42) Eeman, M.; Deleu, M. From Biological Membranes to Biomimetic Model Membranes. *Biotechnol., Agron., Soc. Environ.* **2010**, *14*, 719−736.
(43) Meister, K.; DeVries, A. L.; Bakker, H. J.; Drori, R. Antifreeze Glycoproteins Bind Irreversibly to Ice. *J. Am. Chem. Soc.* **2018**, *140*, 9365−9368.
(44) Liu, Z.; Wang, Y.; Zheng, X.; Jin, S.; Liu, S.; He, Z.; Xiang, J.-F.; Wang, J. Bioinspired Crowding Inhibits Explosive Ice Growth in Antifreeze Protein Solutions. *Biomacromolecules* **2021**, *22*, 2614−2624.
(45) Ishiguro, H.; Rubinsky, B. Mechanical Interactions between Ice Crystals and Red Blood Cells During Directional Solidification. *Cryobiology* **1994**, *31*, 483−500.
(46) Waymouth, C. Osmolality of Mammalian Blood and of Media for Culture of Mammalian Cells. *In Vitro* **1970**, *6*, 109−127.
(47) Matsumoto, S.; Matsusita, M.; Morita, T.; Kamachi, H.; Tsukiyama, S.; Furukawa, Y.; Koshida, S.; Tachibana, Y.; Nishimura, S.; Todo, S. Effects of Synthetic Antifreeze Glycoprotein Analogue on Islet Cell Survival and Function During Cryopreservation. *Cryobiology* **2006**, *52*, 90−98.
(48) Shier, W. T.; Lin, Y.; De Vries, A. L. Structure and Mode of Action of Glycoproteins from an Antarctic Fish. *Biochim. Biophys. Acta* **1972**, *263*, 406−413.
(49) Oude Vrielink, A. S.; Aloi, A.; Olijve, L. L.; Voets, I. K. J. B. Interaction of Ice Binding Proteins with Ice, Water and Ions. *Biointerphases* **2016**, *11*, No. 018906.
(50) Meister, K.; Strazdaite, S.; DeVries, A. L.; Lotze, S.; Olijve, L. L.; Voets, I. K.; Bakker, H. J. Observation of Ice-Like Water Layers at an Aqueous Protein Surface. *Proc. Natl. Acad. Sci. U. S. A.* **2014**, *111*, 17732−17736.
(51) Olijve, L. L. C.; Oude Vrielink, A. S.; Voets, I. K. A Simple and Quantitative Method to Evaluate Ice Recrystallization Kinetics Using the Circle Hough Transform Algorithm. *Cryst. Growth Des.* **2016**, *16*, 4190−4195.
(52) Roke, S.; Schins, J.; Müller, M.; Bonn, M. Vibrational Spectroscopic Investigation of the Phase Diagram of a Biomimetic Lipid Monolayer. *Phys. Rev. Lett.* **2003**, *90*, No. 128101.
(53) Tomczak, M. M.; Hincha, D. K.; Estrada, S. D.; Wolkers, W. F.; Crowe, L. M.; Feeney, R. E.; Tablin, F.; Crowe, J. H. A Mechanism for Stabilization of Membranes at Low Temperatures by an Antifreeze Protein. *Biophys. J.* **2002**, *82*, 874−881.
(54) De Leeuw, F. E.; De Leeuw, A. M.; Den Daas, J. H. G.; Colenbrander, B.; Verkleij, A. J. Effects of Various Cryoprotective Agents and Membrane-Stabilizing Compounds on Bull Sperm Membrane Integrity after Cooling and Freezing. *Cryobiology* **1993**, *30*, 32−44.
(55) Izadyar, F.; Matthijs-Rijsenbilt, J. J.; Den Ouden, K.; Creemers, L. B.; Woelders, H.; de Rooij, D. G. Development of a Cryopreservation Protocol for Type a Spermatogonia. *J. Androl.* **2002**, *23*, 537−545.
(56) Crowe, J. H.; Crowe, L. M.; Carpenter, J. F.; Rudolph, A. S.; Wistrom, C. A.; Spargo, B. J.; Anchordoguy, T. J. Interactions of Sugars with Membranes. *Biochim. Biophys. Acta, Biomembr.* **1988**, *947*, 367−384.

https://doi.org/10.1021/acs.biomac.1c01477
Biomacromolecules 2022, 23, 1214−1220