

# IgG hexamers initiate acute lung injury

Simon J. Cleary<sup>1</sup>, Yurim Seo<sup>1</sup>, Jennifer J. Tian<sup>1</sup>, Nicholas Kwaan<sup>1</sup>, David P. Bulkley<sup>2</sup>, Arthur E. H. Bentlage<sup>3</sup>, Gestur Vidarsson<sup>3</sup>, Éric Boilard<sup>4</sup>, Rolf Spirig<sup>5</sup>, James C. Zimring<sup>6</sup>, Mark R. Looney<sup>1\*</sup>

<sup>1</sup>Department of Medicine, University of California, San Francisco (UCSF), CA, USA.

<sup>2</sup>Department of Biochemistry and Biophysics, University of California, San Francisco (UCSF), CA, USA.

<sup>3</sup>Sanquin Research, Amsterdam, The Netherlands.

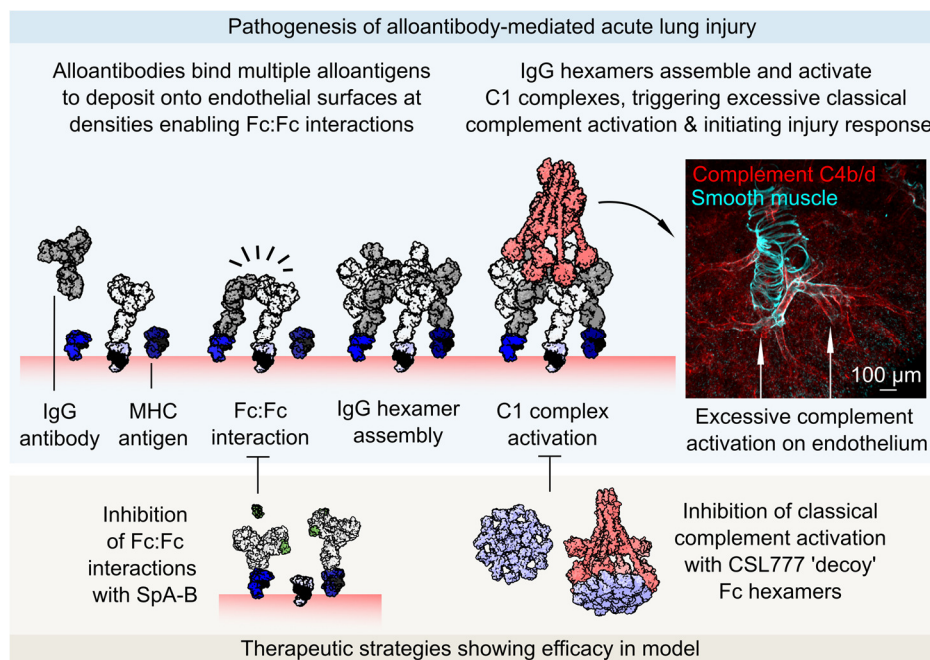
<sup>4</sup>Centre de Recherche du Centre Hospitalier Universitaire de Québec - Université Laval, Québec, QC, Canada.

<sup>5</sup>CSL Behring, Research, CSL Behring Biologics Research Center, Bern, Switzerland.

<sup>6</sup>Department of Pathology, University of Virginia School of Medicine, Charlottesville, VA, USA.

\*Correspondence to: [mark.looney@ucsf.edu](mailto:mark.looney@ucsf.edu)

## Graphical abstract



1 **Abstract**

2 Antibodies can initiate lung injury in a variety of disease states such as autoimmunity, transfusion  
3 reactions, or after organ transplantation, but the key factors determining in vivo pathogenicity of injury-  
4 inducing antibodies are unclear. A previously overlooked step in complement activation by IgG  
5 antibodies has been elucidated involving interactions between IgG Fc domains that enable assembly of  
6 IgG hexamers, which can optimally activate the complement cascade. Here, we tested the in vivo  
7 relevance of IgG hexamers in a complement-dependent alloantibody model of acute lung injury. We  
8 used three approaches to block alloantibody hexamerization (antibody carbamylation, the K439E Fc  
9 mutation, or treatment with domain B from Staphylococcal protein A), all of which reduced acute lung  
10 injury. Conversely, Fc mutations promoting spontaneous hexamerization made a harmful alloantibody  
11 into a more potent inducer of acute lung injury and rendered an innocuous alloantibody pathogenic.  
12 Treatment with a recombinant Fc hexamer 'decoy' therapeutic protected mice from lung injury,  
13 including in a model with transgenic human FCGR2A expression that exacerbated pathology. These  
14 results indicate a direct in vivo role of IgG hexamerization in initiating acute lung injury and the potential  
15 for therapeutics that inhibit or mimic hexamerization to treat antibody-mediated diseases.

16

17 **Brief summary**

18 IgG antibodies can form hexamers. This study shows that hexamer assembly is an important event  
19 determining the ability of IgG to trigger acute lung injury.

## 20 **Introduction**

21 Antibodies and the complement cascade mediate protective immunity but can both become misdirected  
22 to cause harm in autoimmune and alloimmune diseases. Some antibodies can direct activation of the  
23 complement cascade at their targets, an event associated with severe pathology in disease states  
24 including several forms of transfusion reactions (1, 2), immune rejection after solid organ  
25 transplantation (3), and complications of pregnancy (4). Complement-activating alloantibodies are  
26 known mediators of transfusion-related acute lung injury (TRALI) (5, 6), a leading cause of transfusion-  
27 related deaths (7), and are linked to particularly poor outcomes following solid organ transplantation (3,  
28 8). Complement activation by autoreactive antibodies also contributes to pathogenesis of forms of  
29 autoimmune hemolytic anemia (9), small vessel vasculitis (10), and neurological autoimmune disease  
30 (11).

31 Immunoglobulin G (IgG) antibodies are the most prevalent type of antibody in circulation and  
32 complement-activating alloantibodies are frequently IgG class. IgG antibodies achieve complement  
33 activation through recruiting and activating C1 complexes, each of which contain six Fc-binding  
34 domains (12, 13). A theory for how IgG achieves C1 complex activation involves groups of six IgG  
35 antibodies interacting through their Fc domains to form IgG hexamers (14). This theory recently gained  
36 experimental support from direct imaging of IgG1 and IgG3 hexamer assembly on antigenic liposomes  
37 (15, 16), with in vitro studies connecting IgG hexamerization to increased complement deposition on  
38 target surfaces (15, 17, 18). However, it is currently unclear whether IgG hexamer assembly is  
39 important in vivo in the pathogenesis of complement-dependent forms of alloantibody-mediated  
40 disease.

41 Here, we report testing of interventions that exploit IgG hexamerization in a mouse model of acute lung  
42 injury driven by alloantibody deposition in the pulmonary microvasculature, a process that drives  
43 pathology in forms of both TRALI and antibody-mediated rejection (AbMR) of lung transplants (6). Our  
44 results identify key molecular events driving alloantibody-mediated pathophysiology in vivo. We also  
45 demonstrate preclinical efficacy of new therapeutic approaches that prevent pathology of complement-  
46 dependent organ damage caused by alloantibodies, serving as a rationale to pursue translational  
47 studies in human alloantibody driven disease.

## 48 Results

49 Alloantibodies are prevalent but not always harmful, so determining whether alloantibodies are clinically  
50 significant is a frequent conundrum in transfusion and transplantation medicine. Reflecting this clinical  
51 challenge, of the many mouse monoclonal alloantibodies targeting major histocompatibility complex  
52 (MHC) class I antigens, only clone 34-1-2S triggers acute lung injury when microgram quantities are  
53 intravenously injected into mice (19, 20). In addition, only mice expressing the H-2<sup>d</sup> MHC class I  
54 haplotype are known to be susceptible to injury caused by the 34-1-2S antibody (5, 6). Curiously, the  
55 34-1-2S antibody does not readily cause injury in H-2<sup>b</sup> mice, including the widely used C57BL/6 (B6)  
56 strain, despite the fact that it binds to MHC class I antigens expressed by H-2<sup>b</sup> mice (5, 6). We aimed to  
57 measure the affinity of 34-1-2S for a range of MHC class I antigens to improve our understanding of the  
58 factors determining the ability of antibodies to cause injury in both this widely used model and more  
59 generally in antibody-mediated disease states.

60 We measured the binding affinity of 34-1-2S antibody to each of the classical MHC class I antigens  
61 present on injury-resistant H-2<sup>b</sup> B6 mice and injury-susceptible H-2<sup>d</sup> mice (**Fig. 1A**). Of the three MHC  
62 antigens in the H-2 locus (K, D, and L), B6 mice only express K<sup>b</sup> and D<sup>b</sup>, and we detected binding of  
63 34-1-2S to K<sup>b</sup> but not D<sup>b</sup>. In contrast, we detected binding of 34-1-2S to all three MHC class I antigens  
64 from H-2<sup>d</sup> mice, with high affinity binding to K<sup>d</sup> and D<sup>d</sup>, and weak binding to L<sup>d</sup> (**Fig. 1B**). Other MHC  
65 class I antibodies (clones AF6-88.5.5.3, 20-8-4S, SF1.1.10, 30-5-7S and 34-5-8S), which do not readily  
66 induce injury (5)) each bound to only one MHC class I antigen from each MHC type (**Fig. S1**).

67 Together, the above findings led us to the hypothesis that the ability of 34-1-2S to induce lung injury in  
68 H-2<sup>d</sup> mice is a function of increased density of bound antibody in H-2<sup>d</sup> animals resulting from 34-1-2S  
69 simultaneously binding K<sup>d</sup>, D<sup>d</sup>, and possibly L<sup>d</sup>. This hypothesis was tested by injecting 34-1-2S  
70 antibody into B6.ConK<sup>d</sup>-on mice, which express K<sup>d</sup> but do not express D<sup>d</sup> or L<sup>d</sup> (21). B6.H2<sup>d</sup> mice  
71 expressing the full complement of MHC class I antigens recognized by 34-1-2S (K<sup>d</sup>, D<sup>d</sup>, and L<sup>d</sup>) were  
72 used as background-matched positive controls for susceptibility to injury (**Fig. 1C**). In contrast to  
73 B6.H2<sup>d</sup> mice, B6.ConK<sup>d</sup>-on mice did not develop lung injury (**Fig. 1D, E**). These data are consistent with  
74 34-1-2S antibody causing injury in H2<sup>d</sup> mice through high affinity binding to multiple MHC class I  
75 antigens.

76 Engagement of multiple antigens can permit high density antibody deposition, an event associated with  
77 classical complement activation. Complement activation has been implicated in pathogenesis of acute  
78 lung injury caused by 34-1-2S antibody, but previous studies have not determined whether injury in this  
79 model is directly triggered by antibody-mediated complement activation via the classical pathway (5, 6).

80 To test whether 34-1-2S-induced injury requires classical complement activation, we bred mice  
81 expressing the *H2<sup>d</sup>* susceptibility locus with mice lacking C1qa (22), a protein that is necessary for  
82 classical complement activation as it is one of the three proteins which make up each of the six Fc-  
83 binding C1q subcomponents in each C1 complex (**Fig. 2A**).

84 Relative to B6.*H2<sup>d</sup>*:C1qa<sup>+/+</sup> littermate controls, C1qa-deficient B6.*H2<sup>d</sup>*:C1qa<sup>-/-</sup> mice were resistant to  
85 alloantibody-mediated acute lung injury and mortality (**Fig. 2B-D**). Mice lacking C1qa were also  
86 protected from deposition of complement component this C3 split products on the endothelium of  
87 pulmonary capillaries (**Fig. 2E**). Staining for C1qa in lungs confirmed absence of C1qa protein in  
88 knockout mice, with intense C1 complex deposition seen around pulmonary arteriolar endothelial cells  
89 in C1qa-expressing mice injected with 34-1-2S antibody (**Fig. 2F**).

90 To identify the microanatomical site of classical complement activation, we stained lungs of mice  
91 injected with 34-1-2S for the complement split products C4b and C4d, which form covalent bonds with  
92 proteins at sites of classical complement activation. We observed strong positivity for C4b/d highlighting  
93 the endothelium of medium and small-sized pulmonary arterioles in B6.*H2<sup>d</sup>*:C1qa<sup>+/+</sup> mice injected with  
94 34-1-2S, but not in B6.*H2<sup>d</sup>*:C1qa<sup>-/-</sup> mice (**Fig. 2G** and **Movie S1**). Together, these results indicate that  
95 34-1-2S causes acute lung injury because this antibody is deposited onto the pulmonary arteriolar  
96 endothelium at densities sufficient to trigger excessive classical complement activation directed at the  
97 walls of these blood vessels.

98 Dense binding to membrane-expressed antigens would be expected to facilitate IgG Fc:Fc interactions  
99 and IgG hexamer assembly. IgG hexamers are potent activators of C1 complexes in vitro (15), and are  
100 further implicated in classical complement activation by models for C1 complex activation involving  
101 shifting of its six Fc-binding C1q subcomponents into a regular hexagonal configuration (**Fig. 2A, 3A**)  
102 (12, 13). We therefore hypothesized that 34-1-2S assembles into hexamers on the pulmonary  
103 endothelial surface of susceptible mice to trigger complement-dependent acute lung injury.

104 Imaging methods cannot currently resolve IgG hexamers in vivo, but recent studies have developed  
105 methods for inhibiting IgG hexamerization. One approach to impair IgG hexamer assembly is to  
106 carbamylate antibodies, converting lysine residues to homocitrullines to alter charge densities in IgG Fc  
107 regions, inhibiting Fc:Fc interactions and IgG hexamer assembly (**Fig. 3B**) (23). Mice treated with  
108 carbamylated 34-1-2S showed greatly reduced acute lung injury responses compared to littermate  
109 controls treated with non-carbamylated 34-1-2S (**Fig. 3C, D**). Carbamylated 34-1-2S was deposited in  
110 lungs but, in contrast to unchanged 34-1-2S, did not induce complement C3b/d deposition in the  
111 pulmonary microvasculature (**Fig. 3E**)

112 Lysine residues are present on regions of IgG outside of the Fc:Fc interaction interface (illustrated in  
113 **Fig. 3B**), so we pursued a more targeted strategy for inhibition of IgG hexamer assembly. We  
114 determined the sequence of both heavy and light chain complementary-determining regions and  
115 engineered a chimeric antibody with the Fab domain of 34-1-2S fused in frame to human IgG1 (hIgG1-  
116 34-1-2S). To test whether hIgG1-34-1-2S causes injury through hexamerization, we also expressed this  
117 antibody with an Fc point mutation that inhibits Fc:Fc interactions required for IgG hexamer assembly  
118 (K439E, **Fig. 3F**) (15). hIgG1-34-1-2S caused acute lung injury that was reduced by the K439E  
119 mutation (**Fig. 3G, H**), as was complement C4b/d deposition in lungs (**Fig 3I**), lending further support to  
120 a role for Fc:Fc interactions and hexamerization in the pathogenesis of this disease model.

121 We also tested a strategy for pharmacologic inhibition of Fc:Fc interactions by mixing hIgG1-34-1-2S  
122 with recombinant B domains from *Staphylococcus aureus* protein A (SpA-B), which bind to IgG  
123 antibodies near to Fc:Fc interaction sites and inhibit hexamer assembly and complement activation by  
124 antibodies targeting bacterial antigens (**Fig. 3J**) (17, 24). We hypothesized that these properties of  
125 SpA-B, which likely evolved as part of an immune evasion strategy, might be harnessed to prevent  
126 hIgG1-34-1-2S from causing acute lung injury. Adding SpA-B to hIgG1-34-1-2S reduced its ability to  
127 both induce acute lung injury (**Fig. 3K, L**) and cause complement C4b/d deposition within pulmonary  
128 arterioles (**Fig. 3M**). These findings provide a third line of evidence that Fc:Fc interactions leading to  
129 hexamer assembly are important for the injury response caused by this alloantibody.

130 Turning to hexamer gain of function experiments, the introduction of three mutations into the Fc domain  
131 of hIgG1 (RGY mutations: E345R, E430G, S440Y) resulted in antibodies capable of off-target hexamer  
132 assembly as well as increased on-target hexamerization (15) (**Fig. 4A**). We hypothesized that RGY-  
133 mutated 34-1-2S (RGY-hIgG1-34-1-2S) would have enhanced ability to cause acute lung injury due to  
134 increased IgG hexamer formation. We produced RGY-hIgG1-34-1-2S and confirmed its ability to  
135 spontaneously assemble into hexamers in solution (**Fig. 4B**). Consistent with a role for alloantibody  
136 hexamerization in driving injury, RGY-hIgG1-34-1-2S showed increased potency in triggering acute  
137 lung injury relative to hIgG1-34-1-2S (**Fig. 4C, D**), and inducing complement C4b/d deposition in lungs  
138 (**Fig. 4E**). A novel chimeric hIgG1 antibody binding a single MHC class I antigen (hIgG1-Kd1, targeting  
139 K<sup>d</sup>), did not provoke injury when injected into B6.H2<sup>d</sup> mice (**Fig. 4F, G**), consistent with binding to  
140 multiple antigens being a requirement for alloantibody-mediated acute lung injury. However,  
141 introduction of the RGY mutations promoting hexamerization into this innocuous antibody resulted in a  
142 modified version (RGY-hIgG1-Kd1) that was able to provoke increases in lung vascular permeability  
143 and edema (**Fig. 4F & G**). Promoting IgG hexamer assembly can therefore increase in vivo  
144 pathogenicity of alloantibodies.

145 Another approach for therapeutic exploitation of IgG hexamerization involves use of Fc hexamers as  
146 'decoy' treatments. These therapeutic candidates are under investigation as recombinant alternatives to  
147 plasma-derived intravenous or subcutaneous immunoglobulin (IVIg or SClg) treatments that are used in  
148 management of autoimmune and alloimmune diseases (25). We hypothesized that due to its ability to  
149 inhibit classical complement activation (11, 26), the Fc hexamer 'decoy' treatment CSL777 (previously  
150 Fc- $\mu$ TP-L309C) would be effective in preventing alloantibody-mediated acute lung injury.

151 We randomized mice to receive either CSL777, SClg (IgPro20, a human plasma-derived  
152 immunoglobulin product which is currently used to treat antibody-mediated diseases), or vehicle  
153 controls prior to injection with 34-1-2S (**Fig. 5A, B**). Treatment with CSL777 protected mice from  
154 developing 34-1-2S-induced lung vascular permeability and pulmonary edema responses at all doses  
155 tested, whereas treatment with SClg only had a partial effect on alloantibody-induced acute lung injury  
156 responses (**Fig. 5C-F**). CSL777 treated mice lacked alloantibody-mediated deposition of complement  
157 C4 split products on pulmonary arterioles, whereas arteriolar endothelial C4b/d deposition was still  
158 observed in lungs of SClg-treated mice after 34-1-2S antibody injections (**Fig. 5G, H**). Recombinant Fc  
159 hexamer therapeutics such as CSL777 might therefore be useful for prevention or treatment of  
160 complement-dependent forms of alloantibody-mediated organ injury.

161 Unlike humans, mice do not express the Fc $\gamma$  receptor FCGR2A (Fc $\gamma$ RIIA, CD32A), negatively  
162 impacting the predictive value of mouse models for studying human antibody-mediated diseases (27,  
163 28). To test whether our previous findings held up in a system involving FCGR2A-driven pathology, we  
164 crossed existing mouse lines to generate 34-1-2S-mediated injury-susceptible H-2<sup>d</sup> mice expressing a  
165 human FCGR2A (hFCGR2A) transgene (B6.H2<sup>d</sup>:hFCGR2A<sup>Tg/0</sup>). Mice expressing hFCGR2A developed  
166 similar levels of lung injury relative to littermates without hFCGR2A expression but displayed a survival  
167 disadvantage (**Fig. 6A-C**), and increased sequestration of platelets in the pulmonary microvasculature  
168 (**Fig. 6D,E**). Classical complement activation was still critical for pathogenesis in the presence of  
169 hFCGR2A, as knockout of *C1qa* protected mice expressing hFCGR2A from lung injury and mortality  
170 (**Fig. 6F-H**). B6.H2<sup>d</sup>:hFCGR2A<sup>Tg/0</sup> mice treated with CSL777 were protected from 34-1-2S-mediated  
171 injury and showed no mortality responses (**Fig. 6I-K**). These results provide evidence that in a  
172 humanized antibody-mediated acute lung injury model involving pathology driven by hFCGR2A,  
173 classical complement activation is still a critical event in pathogenesis that can be targeted by  
174 therapeutics.

## 175 Discussion

176 This study advances our understanding of immunology in three areas. Our work elucidates the  
177 molecular determinants of susceptibility in a widely used inflammation model. To our knowledge, our  
178 experiments represent the first in vivo evidence that alloantibody hexamerization is important for  
179 pathophysiology. In addition, we show that two experimental therapeutic approaches that target  
180 antibody hexamerization can prevent alloantibody-mediated organ injury.

181 The findings presented in this study allow us to explain a long-standing mystery of great mechanistic  
182 importance in a widely used model of immune-mediated organ injury; in particular, why 34-1-2S  
183 antibody injections (but not injections of other anti-MHC class I antibodies) cause such striking  
184 pathophysiology in mice carrying the H-2<sup>d</sup> but not H-2<sup>b</sup> MHC haplotype (6, 19, 20, 28–38). We posit that  
185 high affinity binding to multiple MHC class I antigens on the pulmonary endothelium of mice with the H-  
186 2<sup>d</sup> haplotype facilitates sufficiently dense alloantibody deposition for IgG hexamer assembly to occur.  
187 These IgG hexamers then direct classical complement activation onto the pulmonary endothelial  
188 surface, initiating the excessive leukocyte and platelet responses that have been reported in previous  
189 studies to cause acute lung injury in this model (6, 19, 20). Furthermore, we were able to render an  
190 innocuous antibody specific for a single MHC class I antigen into a pathogenic antibody by introducing  
191 mutations promoting increased on and off-target hexamerization. An additional implication of our  
192 findings is that both lymphocyte crossmatch and single antigen bead assays for detecting complement-  
193 fixing antibodies may lack sensitivity for detecting antibodies that activate complement in vivo. The  
194 mobility, density and diversity of antigens on the lymphocytes or solid-phase beads used in these  
195 assays does not exactly resemble those on endothelial cell surfaces targeted by donor-specific  
196 antibodies in vivo, and our results indicate that each of these factors determines complement-fixing  
197 capability of antibodies. Conversely, antigen density on beads exceeding that found in vivo may give  
198 false positive findings of complement-fixing antibody responses.

199 By demonstrating that IgG hexamers are important in pathophysiology and represent therapeutic  
200 targets in vivo, our work builds on in vitro studies implicating antibody hexamerization in complement  
201 activation by antibodies targeting antigens on liposomes, lymphoma cells or bacterial membranes (15–  
202 18, 23, 39). Further clinical translation will require determination of the importance of IgG hexamers in  
203 more complex models of diseases involving complement-activating alloantibodies (e.g. AbMR, TRALI,  
204 hemolytic transfusion reactions, and hemolytic disease of the fetus and newborn) or autoantibodies  
205 (e.g. warm autoimmune hemolytic anemia, antiphospholipid syndrome, myasthenia gravis and  
206 neuromyelitis optica). As SpA-B does not inhibit IgG3-mediated complement activation but IgG3 can



207 assemble into hexamers (15, 16), it will also be important to develop strategies to inhibit IgG3  
208 hexamerization to examine the therapeutic potential of targeting hexamers formed by IgG3 antibodies.

209 Our results also provide new insights into the modes of action of past, present, and potential future  
210 therapeutics. Full length staphylococcal protein A (SpA) has been used as a therapeutic in the form of a  
211 now-discontinued extracorporeal immunoadsorption product (Prosorba column). Efficacy of SpA  
212 immunoadsorption has been observed in patients with symptoms unchanged by plasma exchange, an  
213 effect ascribed to leakage of SpA from columns into the bloodstreams of patients resulting in B cell  
214 depletion caused by the action of SpA as a B cell receptor super agonist (40). Purified SpA infusions  
215 (PRTX-100) were subsequently studied in early-stage clinical trials before abandonment for financial  
216 reasons (41). Our results suggest that there may be settings where therapeutics based on the SpA-B  
217 subdomain of SpA have efficacy through preventing complement activation without risk of adverse  
218 effects related to immune complex formation and B cell super agonism caused by immunoglobulin  
219 polyvalency of full-length SpA. Donor-derived immunoglobulin products (e.g. IVIg and SCIg) are  
220 currently used to treat antibody-mediated disease flares. Our observation that SCIg reduces injury  
221 responses but does not prevent classical complement activation in vivo is concordant with previous  
222 studies concluding that immunoglobulin therapeutics act on downstream mediators in vitro and in vivo  
223 (33, 42). CSL777 is an attractive potential future therapeutic for treatment of alloantibody-mediated  
224 diseases as it showed efficacy in our models, and had a mode of action that would be anticipated to  
225 prevent complement activation by both IgM and IgG antibodies as well as pathophysiology resulting  
226 from Fcγ receptors (11, 25, 26). CSL777 also lacks issues with use of donor-derived products related to  
227 sourcing, purification and concentration for injections (25, 43).

228 In conclusion, this study provides evidence that IgG hexamers can be important triggers of  
229 complement-dependent pathophysiology in vivo. Our preclinical studies support further investigation of  
230 IgG hexamerization inhibitors and IgG hexamer ‘decoy’ therapeutics for use in preventing disease  
231 states caused by antibodies and complement activation.

## 232 **Materials and methods**

### 233 *Animals*

234 B6.C-*H2<sup>d</sup>*/bByJ (B6.*H2<sup>d</sup>*) mice (Cat# 000359) (44) and B6(Cg)-*C1qa<sup>tm1d(EUCOMM)Wtsi</sup>*/TennJ (*C1qa<sup>-/-</sup>*) mice  
235 (Cat# 031675) (22) originated from the Jackson Laboratory. B6-background mice were bred with  
236 B6.*H2<sup>d</sup>* mice and progeny were crossed to produce mice with homozygous expression of *H2<sup>d</sup>* MHC  
237 antigens for use in experiments (6). B6.ConK<sup>d</sup>-on and B6.Tg(CD2-Tcra,-Tcrb)75Bucy (TCR75) mice  
238 were provided by J. Zimring (21, 45). BALB/c mice were from Charles River Laboratories (Cat# 028).  
239 B6;SJL-Tg(FCGR2A)11Mkz/J mice (expressing human FCGR2A isoform R131, Jackson Laboratory  
240 Cat# 003542) (27) were backcrossed to B6 congenicity (46). Male mice were used as female mice are  
241 not susceptible to 34-1-2S-mediated injury (5). Mice were studied at 8-16 weeks of age after  
242 maintenance in the UCSF specific pathogen-free animal facility for at least 2 weeks. Procedures  
243 received ethical approval from the UCSF IACUC committee.

### 244 *Surface plasmon resonance*

245 Binding affinities were determined by injecting serial dilutions (0.5-200 nM) of MHC class I monomers  
246 (MBL International Cat#: TB-5001-M (K<sup>b</sup> presenting SIINFEKL); TB-5008-M (D<sup>b</sup> presenting  
247 RAHYNIVTF); TB-M552-M (K<sup>d</sup> presenting VYLKTNVFL); TB-M536-M (D<sup>d</sup> presenting IGPGRAFYA);  
248 TB-M521-M (L<sup>d</sup> presenting SPSYVYHQF)) over monoclonal antibodies bound via amine coupling to  
249 SensEye G Easy2Spot sensors (Ssens Cat# 1-09-04-006), assayed in triplicate with an IBIS MX96  
250 SPR imager.

### 251 *Alloantibody-mediated acute lung injury model*

252 As previously described, mice were given i.p. injections of LPS (Sigma Aldrich Cat# L2880, 0.1 mg/kg)  
253 for 'priming' needed to render barrier-housed mice responsive to antibody injections (19). At 24 hours  
254 after LPS priming, mice were anesthetized (0.6 mg/kg ketamine + 0.1 mg/kg xylazine i.p.) and the  
255 indicated antibody treatments were injected into the jugular vein over the course of 1 minute (at 1  
256 mg/kg unless otherwise stated). Antibodies were from BioXCell (mIgG2a isotype control Cat# BE0085,  
257 34-1-2S Cat# BE0180, hIgG1 isotype control Cat# BE0297) or newly produced (described below). Lung  
258 vascular permeability was measured by giving each mouse 0.01 KBq of <sup>131</sup>I-conjugated albumin (Iso-  
259 Tex Diagnostics, NDC:50914-7731) together with i.v. antibody injections, collecting lungs and blood  
260 samples 2 hours later or at cessation of breathing for radioactivity measurements used to quantify  
261 volume of extravasated plasma in lungs (lung vascular permeability). Wet-dry weight ratios of lungs and  
262 blood were used to calculate excess lung water volumes (6).

263 *Immunofluorescence imaging*

264 Cryosections were made at 200  $\mu\text{m}$  or 400  $\mu\text{m}$  thickness from lungs fixed by inflation with and  
265 immersion in 1% formaldehyde in PBS, as previously described (6). Sections were incubated overnight  
266 with antibodies targeting C3b/d (Novus Cat# NB200-540), C1qa (Abcam Cat# ab182451), C4b/d  
267 (Novus Cat# NB200-541), Scgb1a1 (Sigma Aldrich Cat# ABS1673) or CD41 (Biolegend Cat# 133939)  
268 together with a FITC-conjugated antibody raised against Acta2 (Sigma-Aldrich Cat# F3777) were  
269 incubated overnight at 1:500 with 5% normal donkey serum, 0.1% bovine serum albumin and 0.3%  
270 triton X-100 in phosphate-buffered saline (PBS). After washing, Cy3 or Alexa Fluor 647-conjugated  
271 cross-adsorbed polyclonal secondary antibodies targeting rat, rabbit, goat and/or mouse IgG (Jackson  
272 Immunoresearch Cat# 712-165-153, Cat# 711-165-152, Cat# 705-605-147 and/or Cat# 115-605-206)  
273 were incubated with sections at 1:500 in PBS + 0.3% triton X-100 overnight. After additional washes,  
274 sections were either mounted in Vectashield (Vector Laboratories Cat# H-1700) for standard confocal  
275 imaging on a Nikon A1r microscope, or cleared after staining using the EZ clear protocol (47) for 3D  
276 imaging with a Nikon AZ100M confocal microscope.

277 *Antibody carbamylation*

278 Carbamylation of 34-1-2S was achieved by incubating 1 mg of antibody in PBS + 0.1 M KOCN for 1  
279 hour at 37°C before buffer exchange back into PBS (23). Control 34-1-2S was subjected to the same  
280 process with omission of KOCN.

281 *Antibody sequencing and engineering*

282 The 34-1-2S hybridoma was purchased from ATCC (Cat# HB-79). To generate the Kd1 hybridoma, B6  
283 mice were injected i.v. with  $3 \times 10^6$  CD4+ T cells from TCR75 mice transgenic for a T cell receptor (TCR)  
284 specific for a peptide from K<sup>d</sup> presented by IA<sup>b</sup>, and i.p. with  $5 \times 10^6$  Con-K<sup>d</sup>-on splenocytes, resulting in  
285 an extreme B cell antibody response directed at an immunodominant peptide from K<sup>d</sup>, the only  
286 mismatched antigen between donor and recipient. Three days after a boost with an additional i.p.  
287 injection with Con-K<sup>d</sup>-on splenocytes, splenocytes from the sensitized recipient were fused with a  
288 myeloma cell line as previously described (48), and monoclonal antibodies specific for K<sup>d</sup> were  
289 identified using Con-K<sup>d</sup>-on splenocytes as targets (21).

290 Monoclonal antibody aliquots were digested with either peptidyl-Asp metalloendopeptidase,  
291 chymotrypsin, elastase, trypsin, or pepsin enzymes. Peptides were then assayed using liquid  
292 chromatography coupled to tandem mass spectrometry for sequencing of variable fragments  
293 (Bioinformatics Solutions Inc.). Amino acid sequences determined were, for 34-1-2S:

294 EVQLQQSGAEFVRPGASVKLSCTASGFNLIKDDYMFVWKQRPEQGLEWIGWIAPDNGDTEYASKFQG  
295 KATITADTSSNTAYVQLSSLTSEDVAVYYCTTWGYYSYVNYWGQGTTTLTVSS (heavy chain variable  
296 region) and:  
297 DIQMTQSPSSLSASLGERVSLTCRASQDIGSNLNWLQQEPDGTIKRLIYATYSLDSGVPKRFSGSRSGS  
298 DYSLTISSELESEDFVDYYCLQYASSPYTFGGGTKLEIK (light chain variable region); and for Kd1:  
299 EVLLVESGGDLVKPGGSLKLSAASGFTFRYAMSWVRQTPEKRLEWVATIGDDGSYTFYDPNVKGR  
300 FTISRDNAKNNLYLQMRHLKSEDTAIYFCARDGLFAYWGQGTTLVTVSA (heavy chain variable region)  
301 and:  
302 DIQMTQSPSSLSASLGGKVTITCKASQDIKKNIAWYQYKPGKGPRLLIHYTSTLQPGISSRFSGSGSGR  
303 DYSFISISNLEPEDIATYYCLQYDSLTYTFGGGTKLEIK (light chain variable region). Correct  
304 identification of variable domains was confirmed by performing sequencing of the products of 5' rapid  
305 amplification of cDNA ends (5'-RACE) for heavy and light chain mRNA using RNA isolated from  
306 hybridomas. The isolated 5'-RACE amplicons contained open reading frames that encoded the above  
307 peptides sequenced by mass spectrometry. These sequences were codon-optimized and antibodies  
308 were expressed as chimeric hIgG1 with or without Fc point mutations in a HEK293 cell system and  
309 purified using protein A and buffer exchange (Absolute Antibody).

### 310 *Pharmacologic treatments*

311 Recombinant subdomain B from *Staphylococcus aureus* (SpA-B, amino acid sequence:  
312 HHHHHHADNKFNKEQQNAFYEILHLPNLNEEQRNGFIQSLKDDPSQSANLLAEAKKLNDAAQAPK, His-  
313 tag added for purification) was produced in an *E. coli* system by Genscript and supplied in protein  
314 storage buffer (50 mM Tris-HCl, 150 mM NaCl, 10% Glycerol, pH 8.0). At 1-2 hours before i.v. injection,  
315 SpA-B (3 mg/kg) or vehicle were mixed with hIgG1-34-1-2S resulting in a 30% vehicle, 70% PBS  
316 mixture.

317 Trial formulations of CSL777 (in PBS vehicle), as well as clinical-grade IgPro20 (Hizentra™) and the  
318 proprietary vehicle for IgPro20 were provided by CSL Behring. Mice were given i.p. injections of  
319 CSL777, IgPro20 or relevant vehicle 1-2 hours before i.v. injections of antibodies at stated doses.

### 320 *Negative stain electron microscopy*

321 Antibody samples were diluted to 0.01 mg/ml in 25 mM HEPES, 100 mM NaCl and added to carbon-  
322 coated grids (TedPella Cat# 01702-F, manually coated with 20 nm carbon using a Cressington 208  
323 Sputter Coater). Sample-coated grids were stained using 0.75% uranyl formate and imaged on an FEI  
324 Tecnai T12 transmission electron microscope.

325 *Experimental design and analysis*

326 Within-cage randomization was used for group allocations in studies testing exogenous treatments.  
327 Littermate controls from heterozygous crosses were used to test the effect of *C1qa* knockout. Congenic  
328 animals housed in the same room were used to study haplotype effects. Handlers were blinded to  
329 group allocations during experiments. Group numbers (n) and analysis approaches were  
330 predetermined before initiation of experiments. Statistical tests used on each dataset are described in  
331 figure legends.

332 *Software*

333 GraphPad Prism was used for graphing and statistical analysis. UCSF ChimeraX was used for  
334 molecular graphics (49). Imaris was used to render fluorescence micrographs and ImageJ was used to  
335 process electron microscopy data.

336 **Acknowledgements**

337 Imaging studies were possible thanks to the UCSF Biological Imaging Development Colab, and UCSF  
338 Electron Microscopy core. Sandro Prato (CSL Innovation Pty Ltd, Parkville, Victoria, Australia) provided  
339 advice on in vivo administration of CSL777 and SCIg.

340 **Funding**

341 National Institutes of Health grant R01 HL138673 (JCZ and MRL)  
342 National Institutes of Health grant R35 HL161241 (MRL)  
343 Association for Advancement of Blood and Biotherapies (AABB) Foundation (formerly National Blood  
344 Foundation) Early Career Scientific Research Grant (SJC)  
345 Canadian Institutes of Health Research (ÉB)

346 **Authorship**

347 Conceptualization: SJC, JCZ, MRL  
348 Methodology: SJC, MRL, AEHB, GV, ÉB, RS, JCZ  
349 Investigation: SJC, YS, JJT, NK, DPB, AEHB  
350 Funding acquisition: SJC, JCZ, MRL  
351 Writing – original draft: SJC, MRL  
352 Writing – review & editing: SJC, YS, JJT, NK, DPB, AEHB, GV, ÉB, RS, JCZ, MRL

353 Conflict of interest statement: RS is an employee of CSL Behring AG, Switzerland. The authors have  
354 no additional conflicts of interest.

355 **Data and materials availability**

356 All data are available in the main text or the supplementary materials.

357 **Supplementary materials**

358 Supplementary materials and methods.

359 Supplementary Figures:

360 **Fig. S1. Binding of MHC class I monoclonal antibodies to MHC class I monomers.**

361 **Movie S1. Complement C4 split product deposition in the pulmonary vasculature.**

362 **References**

- 363 1. Vlaar APJ, Juffermans NP. Transfusion-related acute lung injury: a clinical review. *Lancet*.  
364 2013;382(9896):984–994.
- 365 2. Panch SR, Montemayor-Garcia C, Klein HG. Hemolytic Transfusion Reactions. *New England Journal*  
366 *of Medicine*. 2019;381(2):150–162.
- 367 3. Loupy A, Lefaucheur C. Antibody-Mediated Rejection of Solid-Organ Allografts. *New England*  
368 *Journal of Medicine*. 2018;379(12):1150–1160.
- 369 4. Delaney M, Matthews DC. Hemolytic disease of the fetus and newborn: managing the mother, fetus,  
370 and newborn. *Hematology*. 2015;2015(1):146–151.
- 371 5. Strait RT, et al. MHC class I-specific antibody binding to nonhematopoietic cells drives complement  
372 activation to induce transfusion-related acute lung injury in mice. *The Journal of experimental medicine*.  
373 2011;208(12):2525–2544.
- 374 6. Cleary SJ, et al. Complement activation on endothelium initiates antibody-mediated acute lung injury.  
375 *The Journal of Clinical Investigation*. [published online ahead of print: July 30, 2020].  
376 <https://doi.org/10.1172/JCI138136>.
- 377 7. Toy P, et al. Transfusion-related acute lung injury: Incidence and risk factors. *Blood*.  
378 2012;119(7):1757–1767.
- 379 8. Bouquegneau A, et al. Complement-activating donor-specific anti-HLA antibodies and solid organ  
380 transplant survival: A systematic review and meta-analysis. *PLoS Medicine*. 2018;15(5).  
381 <https://doi.org/10.1371/journal.pmed.1002572>.
- 382 9. Berentsen S, Barcellini W. Autoimmune Hemolytic Anemias. *New England Journal of Medicine*.  
383 2021;385(15):1407–1419.
- 384 10. Chen M, Jayne DRW, Zhao M-H. Complement in ANCA-associated vasculitis: mechanisms and  
385 implications for management. *Nat Rev Nephrol*. 2017;13(6):359–367.
- 386 11. Tradtrantip L, et al. Recombinant IgG1 Fc hexamers block cytotoxicity and pathological changes in  
387 experimental in vitro and rat models of neuromyelitis optica. *Neuropharmacology*. 2018;133:345–353.
- 388 12. Mortensen SA, et al. Structure and activation of C1, the complex initiating the classical pathway of  
389 the complement cascade. *Proceedings of the National Academy of Sciences*. 2017;114(5):986–991.
- 390 13. Sharp TH, et al. Insights into IgM-mediated complement activation based on in situ structures of  
391 IgM-C1-C4b. *Proceedings of the National Academy of Sciences*. 2019;116(24):11900–11905.
- 392 14. Burton DR. Antibody: the flexible adaptor molecule. *Trends in Biochemical Sciences*.  
393 1990;15(2):64–69.
- 394 15. Diebold CA, et al. Complement is activated by IgG hexamers assembled at the cell surface.  
395 *Science*. 2014;343(6176):1260–1263.

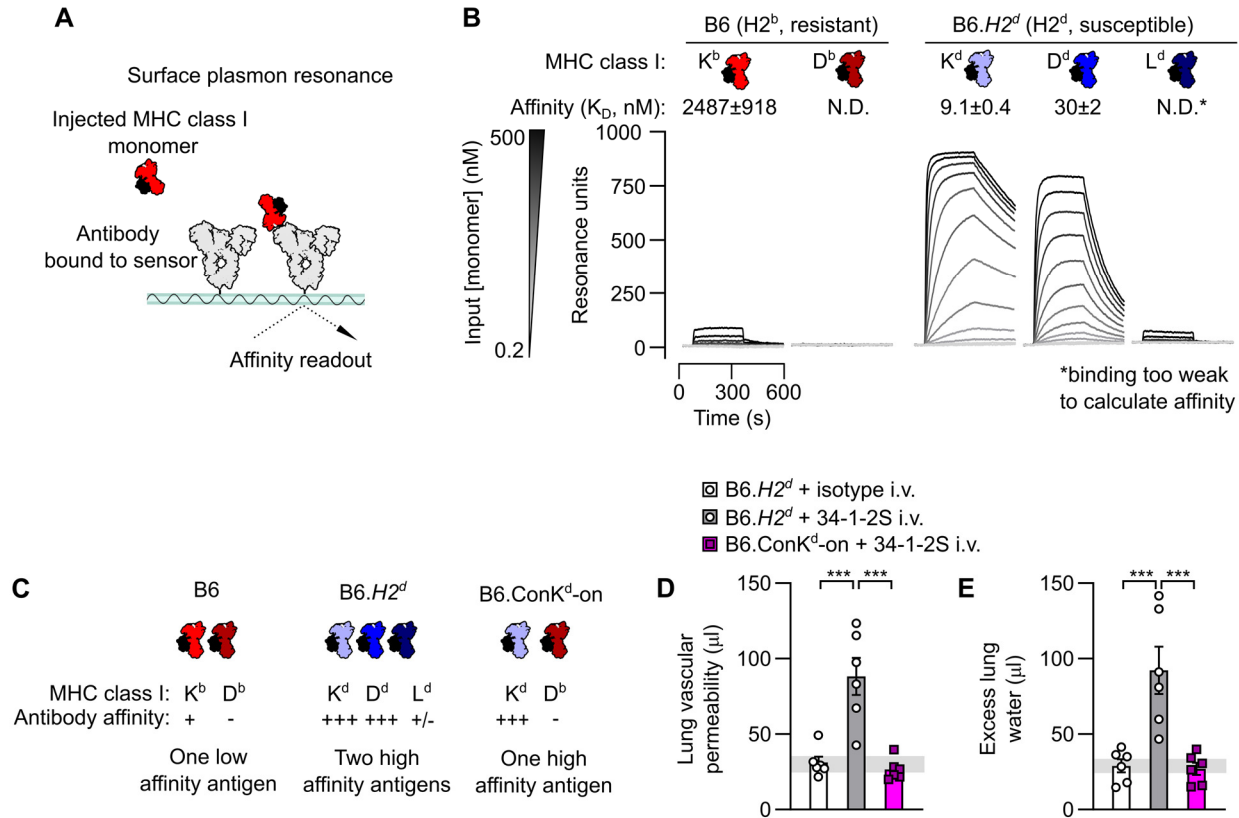
- 396 16. Abendstein L, et al. Complement is activated by elevated IgG3 hexameric platforms and deposits  
397 C4b onto distinct antibody domains. *Nat Commun.* 2023;14(1):4027.
- 398 17. Cruz AR, et al. Staphylococcal protein A inhibits complement activation by interfering with IgG  
399 hexamer formation. *Proc Natl Acad Sci U S A.* 2021;118(7):e2016772118.
- 400 18. de Jong RN, et al. A Novel Platform for the Potentiation of Therapeutic Antibodies Based on  
401 Antigen-Dependent Formation of IgG Hexamers at the Cell Surface. *PLoS Biol.* 2016;14(1):e1002344.
- 402 19. Looney MR, et al. Platelet depletion and aspirin treatment protect mice in a two-event model of  
403 transfusion-related acute lung injury. *Journal of Clinical Investigation.* 2009;119(11):3450–3461.
- 404 20. Looney MR, et al. Neutrophils and their Fc gamma receptors are essential in a mouse model of  
405 transfusion-related acute lung injury. *The Journal of clinical investigation.* 2006;116(6):1615–23.
- 406 21. Hudson KE, et al. Alloimmunogenicity of an isolated MHC allele is affected by the context of MHC  
407 mismatch in a murine model. *Transfusion.* 2019;59(2):744–753.
- 408 22. Fonseca MI, et al. Cell-specific deletion of C1qa identifies microglia as the dominant source of C1q  
409 in mouse brain. *J Neuroinflammation.* 2017;14(1):48.
- 410 23. Lubbers R, et al. Carbamylation reduces the capacity of IgG for hexamerization and complement  
411 activation. *Clinical and Experimental Immunology.* 2020;200(1):1–11.
- 412 24. Ultsch M, et al. 3-2-1: Structural insights from stepwise shrinkage of a three-helix Fc-binding  
413 domain to a single helix. *Protein Engineering, Design and Selection.* 2017;30(9):619–625.
- 414 25. Zuercher AW, et al. Next-generation Fc receptor–targeting biologics for autoimmune diseases.  
415 *Autoimmunity Reviews.* 2019;18(10):102366.
- 416 26. Spirig R, et al. rIgG1 Fc Hexamer Inhibits Antibody-Mediated Autoimmune Disease via Effects on  
417 Complement and FcγRs. *The Journal of Immunology.* 2018;200(8):2542–2553.
- 418 27. McKenzie SE, et al. The Role of the Human Fc Receptor FcγRIIA in the Immune Clearance of  
419 Platelets: A Transgenic Mouse Model. *The Journal of Immunology.* 1999;162(7).
- 420 28. El Mdawar MB, et al. Platelet FcγRIIA-induced serotonin release exacerbates the severity of  
421 transfusion-related acute lung injury in mice. *Blood advances.* 2021;5(23):4817–4830.
- 422 29. Mallavia B, et al. Mirasol pathogen reduction technology treatment of human whole blood does not  
423 induce acute lung injury in mice. *PLOS ONE.* 2017;12(6):e0178725.
- 424 30. Hidalgo A, et al. Heterotypic interactions enabled by polarized neutrophil microdomains mediate  
425 thromboinflammatory injury. *Nat Med.* 2009;15(4):384–391.
- 426 31. Adrover JM, et al. Programmed ‘disarming’ of the neutrophil proteome reduces the magnitude of  
427 inflammation. *Nat Immunol.* 2020;21(2):135–144.
- 428 32. Song D, et al. PTP1B inhibitors protect against acute lung injury and regulate CXCR4 signaling in  
429 neutrophils. *JCI Insight.* 2022;7(14). <https://doi.org/10.1172/jci.insight.158199>.



- 430 33. Semple JW, et al. Intravenous Immunoglobulin Prevents Murine Antibody-Mediated Acute Lung  
431 Injury at the Level of Neutrophil Reactive Oxygen Species (ROS) Production. *PLoS One*.  
432 2012;7(2):e31357.
- 433 34. Hechler B, et al. Platelets are dispensable for antibody-mediated transfusion-related acute lung  
434 injury in the mouse. *Journal of Thrombosis and Haemostasis*. 2016;14(6):1255–1267.
- 435 35. McKenzie CGJ, et al. Peripheral blood monocyte-derived chemokine blockade prevents murine  
436 transfusion-related acute lung injury (TRALI). *Blood*. 2014;123(22):3496–3503.
- 437 36. Sreeramkumar V, et al. Neutrophils scan for activated platelets to initiate inflammation. *Science*.  
438 2014;346(6214):1234–8.
- 439 37. Cadrillier A, et al. Platelets induce neutrophil extracellular traps in transfusion-related acute lung  
440 injury. *J Clin Invest*. 2012;122(7):2661–2671.
- 441 38. Ortiz-Muñoz G, et al. Aspirin-triggered 15-epi-lipoxin A4 regulates neutrophil-platelet aggregation  
442 and attenuates acute lung injury in mice. *Blood*. 2014;124(17):2625–34.
- 443 39. Strasser J, et al. Unraveling the Macromolecular Pathways of IgG Oligomerization and Complement  
444 Activation on Antigenic Surfaces. *Nano Lett*. 2019;19(7):4787–4796.
- 445 40. Silverman GJ, Goodyear CS, Siegel DL. On the mechanism of staphylococcal protein A  
446 immunomodulation. *Transfusion*. 2005;45(2):274–280.
- 447 41. Bussel JB, et al. Safety and Efficacy of PRTX-100, a Highly Purified Form of Staphylococcal Protein  
448 A, in Patients with Immune Thrombocytopenia (ITP). *Blood*. 2016;128(22):4929.
- 449 42. Basta M, Fries LF, Frank MM. High doses of intravenous immunoglobulin do not affect the  
450 recognition phase of the classical complement pathway. *Blood*. 1991;78(3):700–702.
- 451 43. Shock A, Humphreys D, Nimmerjahn F. Dissecting the mechanism of action of intravenous  
452 immunoglobulin in human autoimmune disease: Lessons from therapeutic modalities targeting Fcγ  
453 receptors. *Journal of Allergy and Clinical Immunology*. 2020;146(3):492–500.
- 454 44. Bailey DW. Genetics of histocompatibility in mice. *Immunogenetics*. 1975;2(1):249–256.
- 455 45. Honjo K, et al. Evidence for cooperativity in the rejection of cardiac grafts mediated by CD4 TCR Tg  
456 T cells specific for a defined allopeptide. *Am J Transplant*. 2004;4(11):1762–1768.
- 457 46. Cloutier N, et al. Platelets release pathogenic serotonin and return to circulation after immune  
458 complex-mediated sequestration. *Proceedings of the National Academy of Sciences of the United  
459 States of America*. 2018;115(7):E1550–E1559.
- 460 47. Hsu C-W, et al. EZ Clear for simple, rapid, and robust mouse whole organ clearing. *eLife*.  
461 2022;11:e77419.
- 462 48. Howie HL, et al. Serological blind spots for variants of human IgG3 and IgG4 by a commonly used  
463 anti-immunoglobulin reagent. *Transfusion*. 2016;56(12):2953–2962.
- 464 49. Goddard TD, et al. UCSF ChimeraX: Meeting modern challenges in visualization and analysis.  
465 *Protein Sci*. 2018;27(1):14–25.

466 50. Yuan D, et al. Structure of IgG-Fc hexamer reveals a mutual lock-and-key mode of Fc-Fc  
467 interaction [preprint]. 2022;2022.02.24.481884.

468



469

470

**Fig. 1. The 34-1-2S alloantibody binds to multiple MHC class I antigens to trigger acute lung injury.**

471

**A.** Schematic showing approach for measuring affinity of the MHC class I alloantibody 34-1-2S for MHC class I monomers using surface plasmon resonance (SPR).

472

**B.** SPR sensorgrams showing detection of binding of 34-1-2S to the  $K^b$  MHC class I antigen from  $H2^b$  mice and the  $K^d$ ,  $D^d$  and  $L^d$  antigens from mice with the  $H2^d$  haplotype.

473

**C.** Classical MHC class I antigens present in B6, B6.H2<sup>d</sup> and B6.Con-K<sup>d</sup>-on mice with summary of results from **B**.

474

**D.** Lung vascular permeability and **E.** excess lung water measurements from LPS-primed B6.H2<sup>d</sup> mice given intravenous (i.v.) doses of either 34-1-2S or isotype control, versus B6.Con-K<sup>d</sup>-on mice given i.v. 34-1-2S.

475

Depictions of IgG and MHC class I in **A-C** are based on protein data bank (PDB) entries 1HZH and 1RK1. **B, D & E** show means ± standard errors. Statistical tests used on **D & E** were ordinary one-way ANOVA with Dunnett's test for differences relative to B6.H2<sup>d</sup> + 34-1-2S i.v. group, with data log<sub>10</sub>-transformed prior to analysis, \*\*\* =  $P < 0.0001$ .

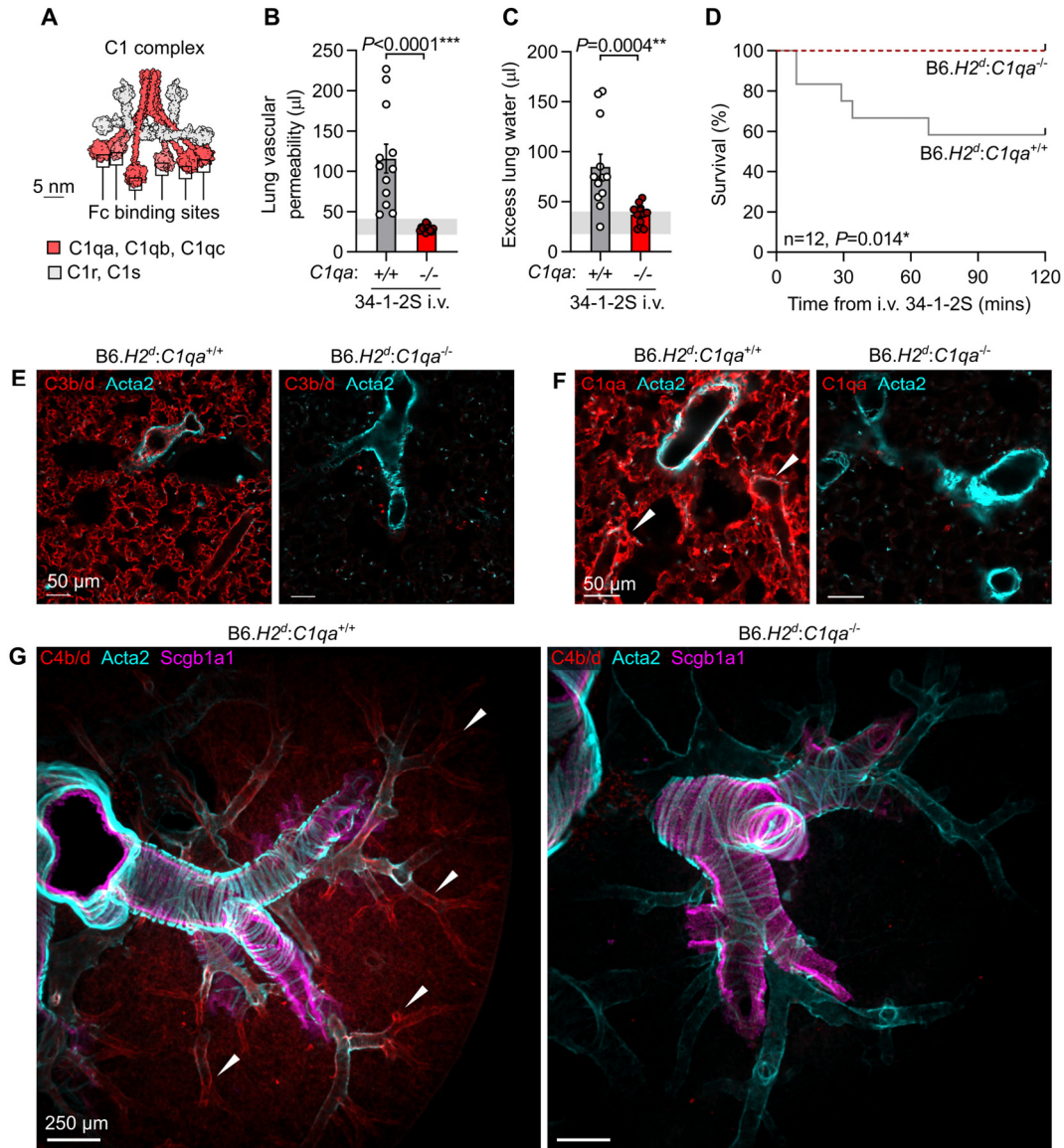
476

477

478

479

480



481

482 **Fig. 2. Classical complement activation on the pulmonary endothelium initiates 34-1-2S-induced acute lung injury.**

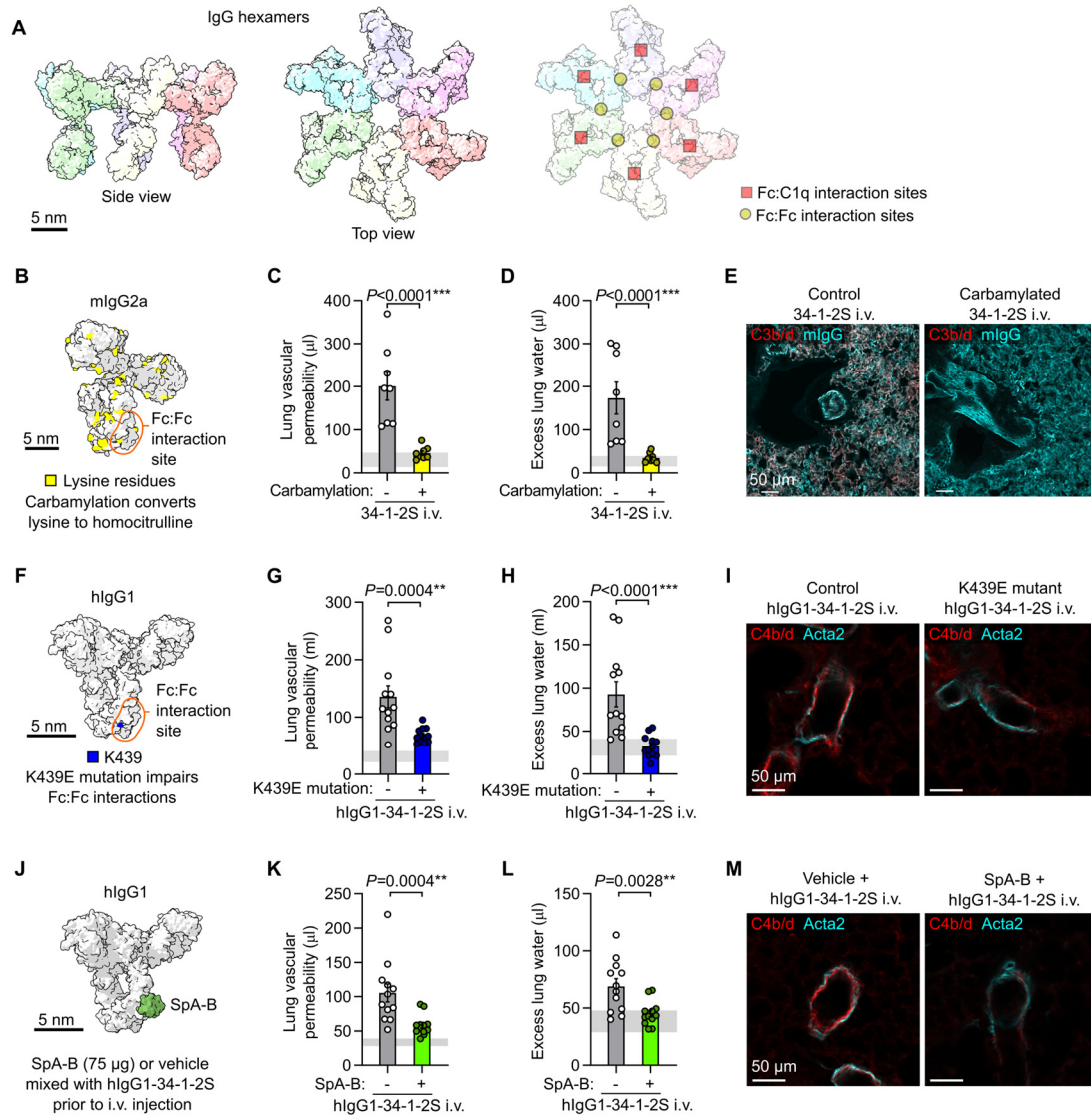
483 **A.** Molecular model of C1 complex based on small angle scattering database entry SASDB38 (12).

484 **B.** Lung vascular permeability and **C.** excess lung water measurements from LPS-primed B6.H2<sup>d</sup>:C1qa<sup>-/-</sup> mice and  
485 B6.H2<sup>d</sup>:C1qa<sup>+/+</sup> littermates given i.v. 34-1-2S at 1 mg/kg. Horizontal gray lines are standard deviations of values from 'no  
486 injury' controls (B6.H2<sup>d</sup> mice given LPS i.p. + mlgG2a isotype control i.v.)

487 **D.** Survival of LPS-primed B6.H2<sup>d</sup>:C1qa<sup>-/-</sup> mice and B6.H2<sup>d</sup>:C1qa<sup>+/+</sup> littermates given i.v. 34-1-2S at 4.5 mg/kg.

488 **E.** Immunofluorescence staining for complement C3b/d, **F.** C1qa or **G.** C4b/d (red) as well as Acta2 (α-smooth muscle actin,  
489 cyan) and, in **G.**, Scgb1a1 (club cell secretory protein, magenta) in lung sections from LPS-primed B6.H2<sup>d</sup>:C1qa<sup>-/-</sup> mice and  
490 B6.H2<sup>d</sup>:C1qa<sup>+/+</sup> mice fixed 5 minutes after i.v. 34-1-2S at 1 mg/kg. Images in **G.** are maximum intensity projections sampling  
491 240 µm from a cleared thick section. White arrowheads point to arterioles positive for complement components.

492 **B & C** show means ± standard errors. *P*-values are from unpaired two-tailed *t*-tests on log<sub>10</sub>-transformed data (**B & C**) or log-  
493 rank test (**D**), with group n=12.



494

495 **Fig. 3. Inhibiting IgG hexamer assembly reduces 34-1-2S-induced acute lung injury responses.**

496 **A.** Molecular models of IgG hexamers based on PDB entry 1HZH, showing Fc:Fc and Fc:C1q interaction sites.

497 **B.** Molecular model showing lysine residues in mouse IgG2a (mIgG2a), PDB entry 1IGT.

498 **C.** Lung vascular permeability, **D.** excess lung water measurements and **E.** lung complement C3b/d and mIgG immunostains  
499 from LPS-primed BALB/c mice after i.v. injection of carbamylated or control 34-1-2S.

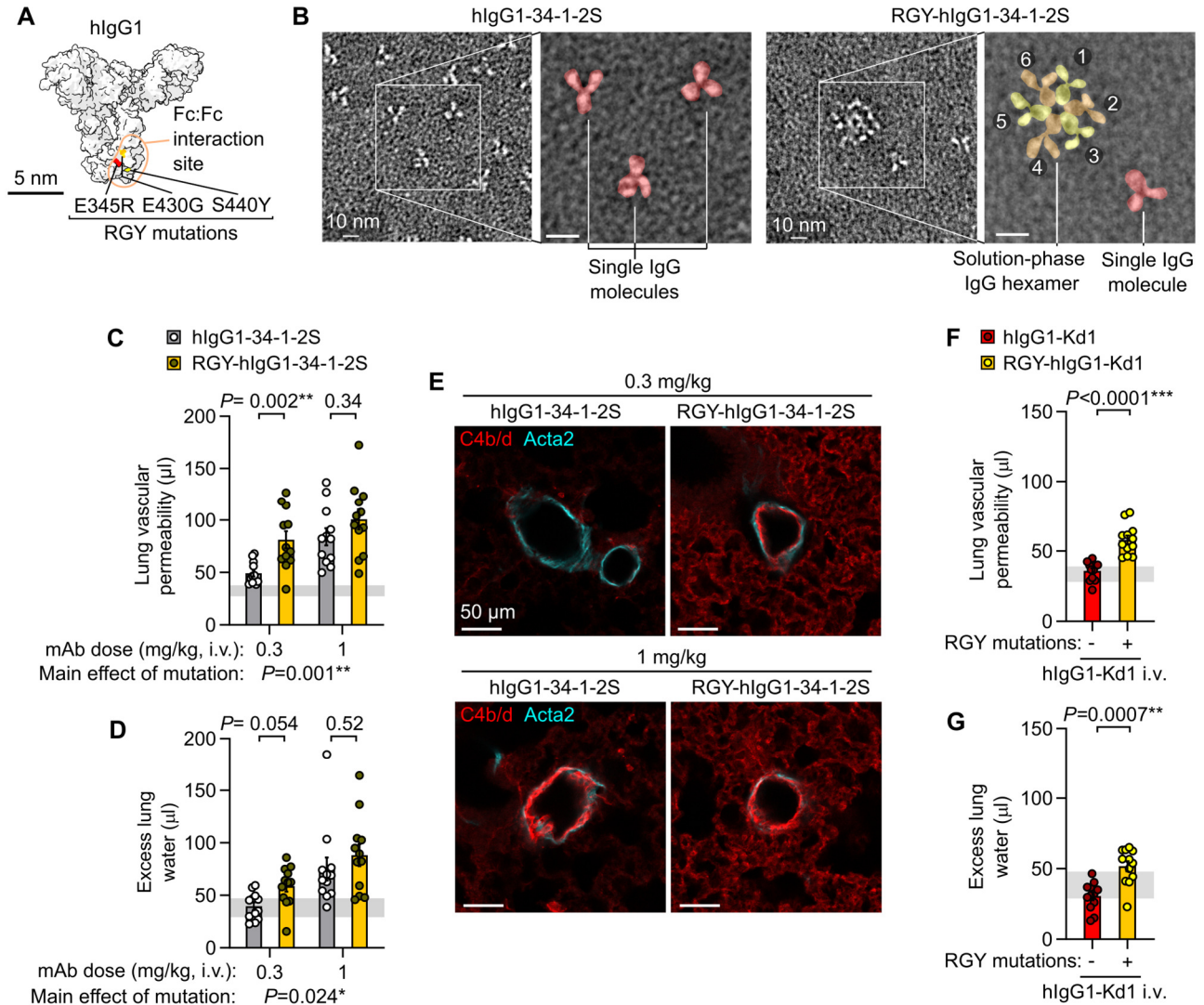
500 **F.** Molecular model showing location of Fc domain lysine 439 (K439) in human IgG1 (hIgG1), PDB entry 1HZH.

501 **G.** Lung vascular permeability, **H.** excess lung water measurements and **I.** lung complement C4b/d and Acta2 immunostains  
502 from LPS-primed B6.H2<sup>d</sup> mice after i.v. injection with hIgG1-34-1-2S or hIgG1-34-1-2S with K439E mutation.

503 **J.** Molecular model showing binding site of SpA-B to Fc domain of human IgG1 (hIgG1), PDB entries 1HZH and 5U4Y.

504 **K.** Lung vascular permeability, **L.** excess lung water measurements and **M.** lung complement C4b/d and Acta2 immunostains  
505 from LPS-primed B6.H2<sup>d</sup> mice after i.v. injection with hIgG1-34-1-2S either mixed with 75 µg SpA-B or vehicle control.

506 Samples for injury measurements were collected at 2 hours after antibody injections and lungs were fixed for immunostaining  
507 at 5 minutes after antibody injections. Graphs show means ± standard errors. *P*-values are from unpaired two-tailed *t*-tests on  
508 log<sub>10</sub>-transformed data, with group *n*=8 (**C, D**) or *n*=12 (**G, H, K, L**).



509

510 **Fig. 4. Fc mutations promoting IgG hexamer assembly increase in vivo pathogenicity of alloantibodies.**

511 **A.** Molecular model showing amino acids mutated in RGY-hlgG1 antibodies, based on PDB entry 1HZH.

512 **B.** Negative stain electron micrographs showing single hlgG1-34-1-2S molecules and spontaneous solution-phase hexamers  
513 formed by RGY-hlgG1-34-1-2S (colored overlay highlights structures in expanded images).

514 **C.** Lung vascular permeability and **D.** excess lung water measurements from LPS-primed B6.*H2<sup>d</sup>* mice injected with control or  
515 RGY-mutated hlgG1-34-1-2S monoclonal antibodies (mAbs) at i.v. doses of either 0.3 or 1 mg/kg.

516 **E.** Immunofluorescence staining showing pulmonary arterioles stained for complement C4b/d (red) and Acta2 (cyan) in lung  
517 sections from LPS-primed B6.*H2<sup>d</sup>* mice given indicated treatments, with samples fixed 5 minutes after antibody injections.

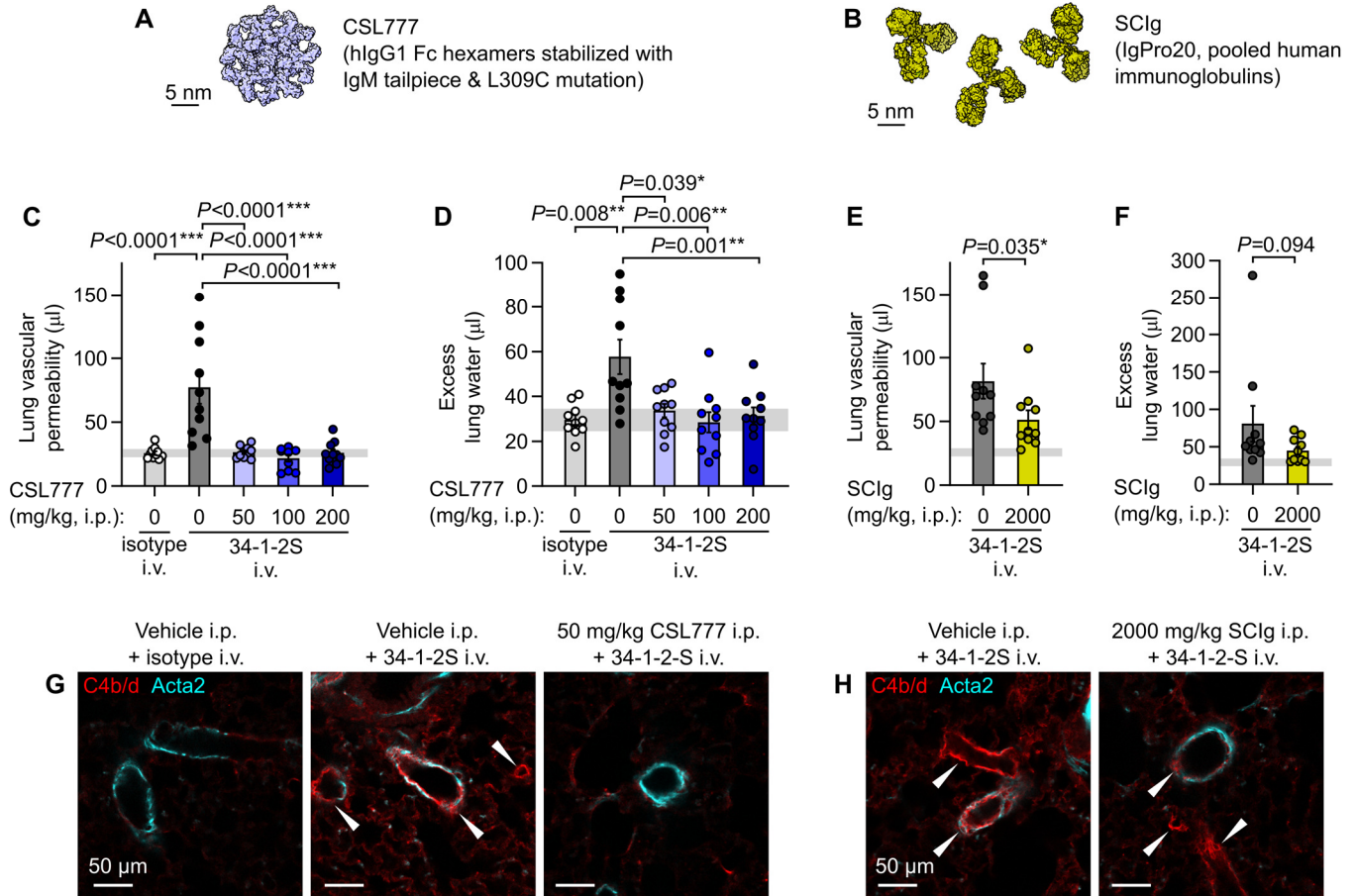
518 **F.** Lung vascular permeability and **G.** excess lung water measurements from LPS-primed B6.*H2<sup>d</sup>* mice injected with control or  
519 RGY-mutated hlgG1-Kd1 (a novel mAb targeting only the H-2K<sup>d</sup> MHC class I antigen) at 1 mg/kg i.v..

520 Graphs show means  $\pm$  standard errors with horizontal line representing standard deviations from 'no injury' controls (LPS-

521 primed B6.*H2<sup>d</sup>* mice given hlgG1 isotype control i.v.). Log<sub>10</sub>-transformed data were analyzed using an ordinary two-way

522 ANOVA with Šidák's multiple comparisons test for effect of Fc mutation within dose level (**C**, **D**) or unpaired two-tailed t-test (**F**,

523 **G**), with group n=12.



524

525 **Fig. 5. Treatment with recombinant Fc hexamer decoys prevents alloantibody-mediated acute lung injury.**

526 **A.** Molecular representation of CSL777, an investigational recombinant Fc hexamer ‘decoy’ treatment which inhibits classical  
527 complement activation, based on PDB entry 7X13 (50).

528 **B.** Molecular representation of SCIg, a pooled human immunoglobulin therapeutic with anti-inflammatory properties at high  
529 doses, based on PDB entry 1HZH.

530 **C.** Lung vascular permeability and **D.** excess lung water measurements from LPS-primed BALB/c mice given i.p. vehicle or  
531 CSL777 at indicated doses 1 hour before i.v. injection with 34-1-2S or mIgG2a isotype control.

532 **E.** Lung vascular permeability and **F.** excess lung water measurements from LPS-primed BALB/c mice given i.p. vehicle or  
533 2000 mg/kg SCIg 1 hour before i.v. injection with 34-1-2S or mIgG2a isotype control.

534 **G.** and **H.** Immunofluorescence showing pulmonary arterioles stained for complement C4b/d (red) and Acta2 (cyan) in lung  
535 sections from LPS-primed BALB/c mice given indicated treatments, with samples fixed 5 minutes after antibody injections.

536 White arrowheads point to arterioles with endothelial positivity for C4b/d.

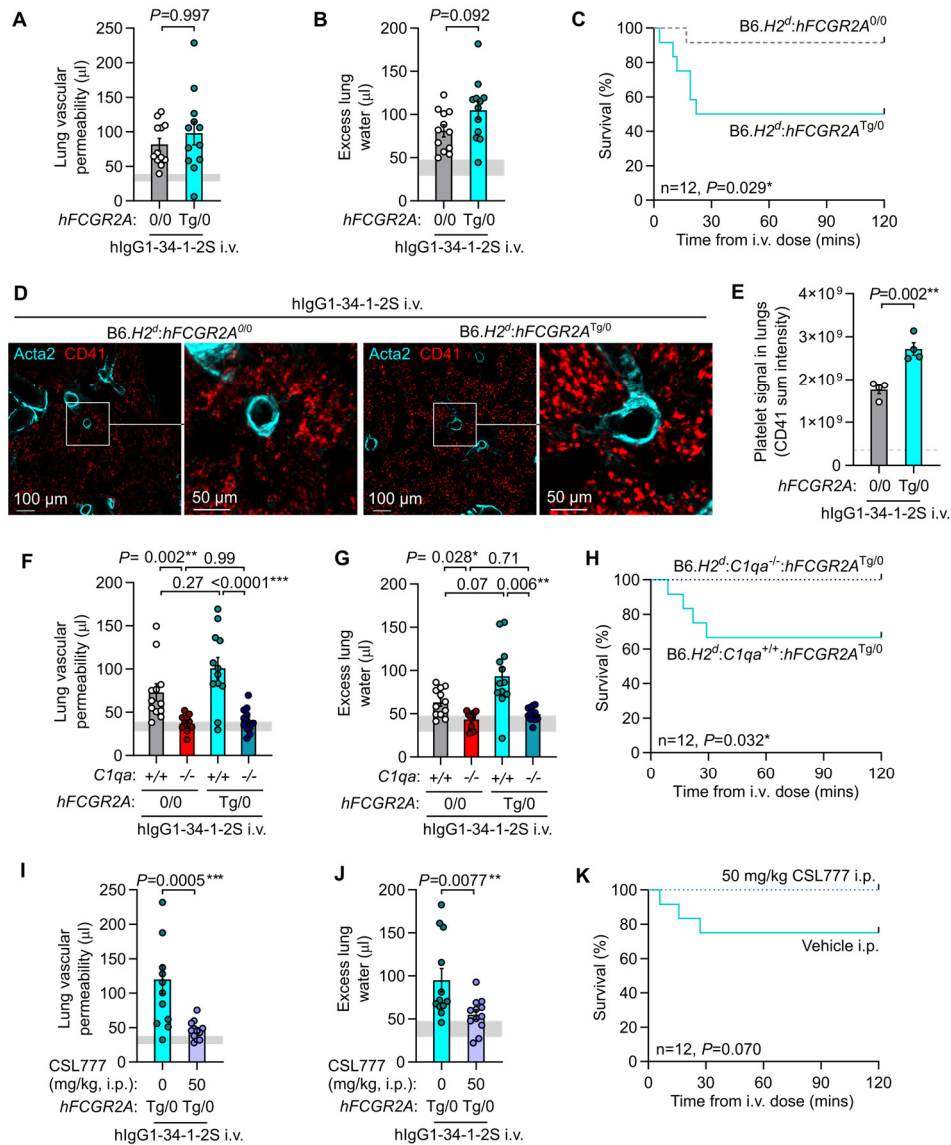
537 Graphs show means  $\pm$  standard errors with horizontal line representing standard deviations from ‘no injury’ controls (from

538 vehicle + isotype control group). Log<sub>10</sub>-transformed data were analyzed using either (**C, D**) an ordinary one-way ANOVA with

539 *P*-values from Dunnett's multiple comparisons test for difference relative to vehicle + 34-1-2S group, or (**E, F**) two-tailed

540 unpaired t-test, with group *n*=10.

541



542

543 **Fig. 6. Acute lung injury is complement-dependent in a model incorporating human FCGR2A-mediated pathology.**

544 **A.** Lung vascular permeability, **B.** excess lung water and **C.** survival readouts from LPS-primed  $B6.H2^d:hFCGR2a^{Tg/0}$  mice and

545  $B6.H2^d$  littermate controls given i.v. hlgG1-34-1-2S at 1 mg/kg.

546 **D.** Immunofluorescence imaging of platelet sequestration (CD41, red, with Acta2 in cyan) in lungs from  $B6.H2^d:hFCGR2a^{Tg/0}$

547 mice and littermates without hFCGR2A fixed at 20 minutes after hlgG1-34-1-2S injections, quantified in **E.**

548 **F.** Lung vascular permeability, **G.** excess lung water and **H.** survival readouts from LPS-primed  $B6.H2^d:C1qa^{+/+}$  and

549  $B6.H2^d:C1qa^{-/-}$  mice, as well as littermates of each genotype expressing hFCGR2A, given i.v. hlgG1-34-1-2S at 1 mg/kg.

550 **I.** Lung vascular permeability, **J.** excess lung water and **K.** survival readouts from LPS-primed  $B6.H2^d:hFCGR2a^{Tg/0}$  mice given

551 either vehicle or 50 mg/kg CSL777 i.p. before i.v. hlgG1-34-1-2S at 1 mg/kg.

552 **A, B, E, F, G, I & J** show means  $\pm$  standard errors with horizontal gray lines showing means or standard deviations of values

553 from 'no injury' controls ( $B6.H2^d$  mice given LPS i.p. + hlgG1 isotype control i.v.) and were log<sub>10</sub>-transformed prior to analysis.

554  $P$ -values are from: (**A, B, I, J**) unpaired, two tailed t-tests; (**F, G**) two-way ANOVA with Šidák's multiple comparisons test; or

555 (**C, H, K**) log-rank test, with group  $n=4$  (**E**) or 12 (other graphs).