Modulation of ligand-gated glycine receptors via functional monoclonal antibodies

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List of Non-Standard Abbreviations:

BBB – blood brain barrier
BCA – bicinchoninic acid
CNS – central nervous system
DDM - n-dodecyl β-D-maltoside
EBD – extracellular binding domain
FAB – fragmented monoclonal antibody
FACS – fluorescence-activated cell sorting
FLIPR – fluorescence imaging plate reader
GlyRs - glycine receptors
GlyRα3 – homopentameric glycine receptor alpha 3
GlyRα1 – homopentameric glycine receptor alpha 1
GlyRα3β – heteropentameric glycine receptor alpha 3 with beta subunits
GlyRα1β – heteropentameric glycine receptor alpha 1 with beta subunits
HTS – high-throughput screening
ICF - immunocytofluorescence
mAb – full-length monoclonal antibody
MP – membrane potential
POC – percent of control
SPR – surface plasmon resonance
THC - Δ9-tetrahydrocannabinol
TM - transmembrane
Abstract

Ion channels are targets of considerable therapeutic interest to address a wide variety of neurological indications, including pain perception. Current pharmacological strategies have focused mostly on small molecule approaches which can be limited by selectivity requirements within members of a channel family or superfamily. Therapeutic antibodies have been proposed, designed and characterized to alleviate this selectivity limitation, however there are no FDA-approved therapeutic antibody-based drugs targeting ion channels on the market to date. Here, in an effort to identify novel classes of engineered ion channel modulators for potential neurological therapeutic applications, we report the generation and characterization of six ($EC_{50} < 25 \text{nM}$) Cys-loop receptor family monoclonal antibodies with modulatory function against rat and human glycine receptor alpha 1 (GlyRα1) and/or GlyRα3. These antibodies have activating (i.e.; positive modulator) or inhibiting (i.e.; negative modulator) profiles. Moreover, GlyRα3 selectivity was successfully achieved for two of the three positive modulators identified. When dosed intravenously, the antibodies achieved sufficient brain exposure to cover their calculated \textit{in vitro} $EC_{50}$ values. When compared head-to-head at identical exposures, the GlyRα3-selective antibody showed a more desirable safety profile over the non-selective antibody, thus demonstrating, for the first time, an advantage for GlyRα3-selectivity. Our data show that ligand-gated ion channels of the glycine receptor family within the CNS can be functionally modulated by engineered biologics in a dose-dependent manner and that, despite high protein homology between the alpha subunits, selectivity can be achieved within this receptor family resulting in future therapeutic candidates with more desirable drug safety profiles.
**Significance Statement**

We present immunization and multi-platform screening approaches to generate a diverse library of functional antibodies (agonist, potentiator or inhibitory) raised against human glycine receptors (GlyRs). We also demonstrate the feasibility of acquiring alpha subunit selectivity, a desirable therapeutic profile. When tested *in vivo*, these tool molecules demonstrated an increased safety profile in favor of GlyRα3-selectivity. To our knowledge, these are the first reported functional GlyR antibodies that may open new avenues to treating CNS diseases with subunit selective biologics.
Introduction

Ion channels play a critical role in membrane excitability, secretion, cell migration, and gene transcription. Indeed, more than 400 ion channel genes have been identified to date (Overington et al., 2006; Bagal and Bungay, 2012), making them an important target-class for drug discovery. Many have been validated as potential therapeutic targets covering a vast array of neuronal diseases. Small molecule approaches have been favored for centrally located targets due to the requirement of crossing the blood brain barrier (BBB), but peripherally restricted ion channels have been interrogated with biologics such as functional (inhibiting) antibodies or biological toxins (Beck et al., 2010; Bosmans and Swartz, 2010). To date, no approved therapeutic antibody-based molecule has been developed for ion channels, reiterating the difficulties of such an approach and the associated limitations with methods of delivery. In particular, we focus on the near absence of functional therapeutic antibodies for glycine receptors (GlyRs).

Glycine receptors (GlyRs) are chloride-conducting ion channels belonging to the Cys-loop superfamily and are comprised of five subunits arranged into pentamers around a central ion pore with ligand binding sites located at subunit domain interfaces (Hibbs and Gouaux, 2011; Huang et al., 2015). Each subunit consists of a large extracellular binding domain (EBD) and four transmembrane (TM) helices with the TM2 helix lining the central pore cavity. The alpha (α) subunits are required for functional chloride conductivity (Betz and Laube, 2006). All α isoforms can arrange into homomeric pentamers or combine with beta (β) subunits to form heteromeric Glyαβ channels. Although expression of the β subunit alone does not lead to a functional channel, the β subunit has been shown to modulate agonist affinities and interact strongly with the intracellular protein gephyrin to facilitate post-synaptic clustering of GlyR heteropentamers (for review see (Tyagarajan and Fritschy, 2014; Burgos et al., 2016)). The protein sequences of the full-length human GlyRα1 and α3 subunits are ~93% similar, with the
sequence identity increasing to ~97% within the EBD, making selective targeting of these receptors challenging. For this reason, selective tools necessary to characterize these various channel subtypes, and better resolve their precise pharmacology have been lacking.

In the CNS, glycine is one of two major inhibitory neurotransmitters modulating transduction of both sensory and motor signals. Glycinergic interneurons synapse onto second order spinal neurons that receive direct input from peripheral sensory neurons (of which cell bodies are located in the dorsal root ganglia) and have been demonstrated to be key players in the modulation of pain and itch processing (Foster et al., 2015). Their enriched distribution in the spinal cord and brainstem makes them an attractive therapeutic target class for modulation of neuronal circuitry (Harvey et al., 2004). Indeed, GlyRα3 has been reported to be implicated in the processing of inflammatory pain (Ahmadi et al., 2002; Harvey et al., 2004; Lynch and Callister, 2006; Werynska et al., 2021) and its potential therapeutic role in a wider variety of pain perception (including chronic pain) has been demonstrated by the analgesic effects of cannabis and its primary psychoactive component Δ9–tetrahydrocannabinol (THC) (Hejazi et al., 2006; Xiong et al., 2011), as well as positive allosteric modulation of GlyRs in a model of neuropathic pain (Bregman et al., 2017; Huang et al., 2017) (also see reviews: (Zeilhofer et al., 2018; Zeilhofer et al., 2021)). Additional reported positive modulators of GlyRs include divalent cations (e.g. Zn\(^{2+}\)), glutamatergic ligands, neuroactive steroids, general anesthetics, n-alcohols and propofol derivatives, plant alkaloids, such as tropeines and gelsimine and ginkolic acid (Yevenes and Zeilhofer, 2011; Maleeva et al., 2015b; Maleeva et al., 2015a; Shalaly et al., 2015). Conversely, the GlyR antagonist strychnine heightens painful response by blocking stimulation of inhibitory pain control pathway by glycine (Beyer et al., 1985; Yaksh, 1989; Loomis et al., 2001).

Here, we report the generation and characterization of six rat/human GlyRs mouse monoclonal antibodies with positive and negative receptor modulation profiles. The ability of these antibodies to modulate GlyRα3/1(β) subtypes or to selectively modulate GlyRα3 activity was demonstrated via an in...
vitro cell-based membrane potential (MP) dye HTS assay using corresponding human (HEK293T) stable cell lines. In addition, we demonstrate that selectivity favoring GlyRα3 over GlyRα1 offers a more desirable safety profile when dosed head-to-head in vivo (in rats) at the same dose and exposure. These new tools, combined with our current understanding of chronic pain-related CNS target engagement for GlyRs, support the investigation of selective monoclonal antibody approaches to target these receptors.
Materials & Methods

**Generation of stable human GlyR cell lines.** HEK293T cells stably expressing full-length human GlyRα3β, GlyRα1β, GlyRα1 or GlyRα3 were used in these studies and have been described previously (Huang et al., 2015; Huang et al., 2017). Briefly, the α3, α1, and β subunits of the human glycine receptor were individually subcloned into the pcDNA3.1 vectors, containing various antibiotic selection cassettes (Thermo Fisher Scientific, Waltham, MA) and stably transfected into HEK293T cells grown in cell culture medium (DMEM supplemented with 10% v/v heat-inactivated FBS, 100 units Penicillin, 100 units streptomycin, 29.2 mg/mL of L-glutamine). During the clonal selection, picrotoxin was utilized to characterize the GlyR homopentameric and heteromeric cell lines and confirmed the absence of significant native GlyR β subunit proteins, which have been reportedly expressed in HEK293 cells (Thomas and Smart, 2005). Despite being expressed in the same HEK293T cellular background, we observed a ~1000X weaker picrotoxin inhibition potency in cells expressing heteropentameric GlyRα3β compared to cells expressing homopentameric GlyRα3. While we cannot rule out the presence of trace levels of endogenous GlyR β subunit proteins, the picrotoxin results suggest that their influence on GlyR channel profiles is not significant.

For screening purposes, the cells were cultured and prepared as follows. Following 48-72 hours of incubation at 37 °C, 5 % v/v CO₂ and 95% humidity, cells were seeded using single cell dilution into 96 well plates containing cell culture media with the corresponding antibiotic selection; cells transfected with subunit α3 and α1 DNA were selected using Hygromycin, and the β subunit expressing cells were selected using 100 μg/mL Zeocin (Thermo Fisher Scientific, Waltham, MA). The stable clones were expanded in fresh medium containing selective antibiotic. Protein expression was confirmed by western blot and functional assay testing.
**Human GlyRα3 and GlyRα1 protein constructs, expression, and purification.** Expression and purification of homopentameric human GlyRα3 and GlyRα1 protein was carried out as described previously (Huang et al., 2015; Huang et al., 2017), using the Bac-to-Bac system (Life Technologies). Briefly, the recombinant baculoviruses containing mammalian GlyRα3 or GlyRα1 sequences were generated, and expression was carried out in baculovirus transduced Sf9 insect cells grown in SFX-Insect Cell Culture Medium (Hyclone) at 27 °C for 72 hr. Cells were harvested by centrifugation, disrupted in a microfluidizer and the homogenate was clarified by centrifugation at 10,000g. Crude membranes were then collected by centrifugation at 125,000g. The membranes were mechanically homogenized and solubilized in 0.2 g n-dodecyl β-D-maltoside (DDM) per gram of membranes in 20 mM Tris pH 8.0, 150 mM NaCl, 0.5 % protease inhibitors cocktail and then centrifuged again at 125,000g. The supernatant was bound to strep affinity resin (IBA GmbH), washed with 20 mM Tris pH 8.0, 150 mM NaCl, 1 mM DDM and eluted with 20 mM Tris pH 8.0, 150 mM NaCl, 1 mM DDM, and 5 mM desthiobiotin. Eluted protein fractions were pooled together, concentrated, and further purified by gel filtration in 20 mM Tris pH 8.0, 150 mM NaCl, and 1 mM DDM. All purification steps were performed at 4 °C.

**Generation of full-length and fragmented (FAb) monoclonal antibodies.** Mouse monoclonal antibodies were originally generated against human GlyRα3 protein for the intended purpose of stabilizing purified GlyR proteins for crystallization. Recombinantly expressed and purified human GlyRα3 in detergent micelles was used to immunize adult wild type mice and initial hybridoma screening was done by native ELISA using Ni-NTA plates (Qiagen) and buffers containing detergent. To limit the number of antibodies recognizing linear epitopes, hybridomas that showed response against 8 M urea denatured protein were eliminated. Specificity of the antibody for properly folded GlyRα3 was assayed by fluorescent-detection size-exclusion chromatography FSEC, assessing in-solution binding to a GlyRα3 - green fluorescent protein (GFP) fusion. GFP was incorporated in the loop between transmembrane helices 3 and 4. Finally, to further eliminate hybridomas that bind to linear epitopes, those that showed signal in SDS-
PAGE western blots against GlyRα3 were also eliminated. Hybridoma cell lines were dilution cloned to ensure monoclonality. A total of six monoclonal antibodies were generated and each was purified from supernatants by mercaptoethylpyridine and protein A chromatography. FAb fragments were generated by papain digestion and purified by ion exchange chromatography to remove Fc and undigested material.

To facilitate the investigation of these antibodies on GlyR channel function described here, molar concentrations were determined by first measuring the concentration of each stock solution using either a Bradford or bicinchoninic acid (BCA) assay and extrapolating stock concentration value from a bovine serum albumin (BSA) standard curve followed by the UV absorbance at 280nm ($A_{280}$) measurement of a serially diluted antibody or FAb to determine the molar extinction coefficient ($\varepsilon$). The molar extinction coefficient was calculated by plotting $A_{280}$ versus concentration and taking the slope of a linear fit. Working solutions of each antibody or FAb were made fresh prior to each experiment and concentrations were determined using Beer’s Law and the respective experimentally determined molar extinction coefficient values. A full list of fragmented and full-length mouse monoclonal antibodies against human GlyR can be found in Table 1.

**Functional testing in FLIPR assay.** We applied a high-throughput FLIPR Membrane Potential (MP) Dye Assay (Jensen and Kristiansen, 2004) to assess the ability of GlyR antibodies and FAbs to modulate the net membrane potential of GlyR expressing HEK293T cells as described previously (Huang et al., 2015; Huang et al., 2017). Briefly, HEK293T cells stably expressing full-length human GlyRα1β, GlyRα3β, GlyRα1 or GlyRα3 were cultured in cell culture medium (MEM supplemented with 10% v/v qualified heat-inactivated FBS, 100 units penicillin, 100 units streptomycin, 29.2 mg/mL of L-glutamine) under standard cell culture conditions of 37 °C, 5 % v/v CO₂ and 95 % humidity. Cells were grown in T 225 cm² culture flasks to a density of approximately $8 \times 10^7$ cells and harvested after approximately 4 days by
briefly washing with DPBS followed by addition of Cell Dissociation Buffer (enzyme-free PBS; Gibco, Waltham, MA) for 2 min. Alternatively, rat GlyRα1 or GlyRα3 were transiently expressed in HEK293T cells using BacMam system. Parental HEK293T cells were cultured and harvested as described above, followed by incubation with a titered baculovirus stock to enable transient overnight expression of each rat channel subtype. For all assays, the concentration of cells in suspension was adjusted to 4.80 x 10^5 cells/mL in cell plating medium (MEM with 10% dialyzed FBS, 100 units Penicillin, 100 units streptomycin, 0.29 mg/mL of L-glutamine and 10 mM HEPES pH 7.4). Using a Multidrop Combi, 25 μL of cell suspension (stably (human) or transiently (rat) expressing GlyRs) was dispensed into Corning CellBIND® 384-well ViewPlates. Cell culture plates were then incubated at 37 °C overnight under the standard cell culture conditions described above. The next day (~18-24 hr after plating), 5 μL of 6X Membrane Potential (MP) blue dye for monitoring changes in membrane potential was dispensed into each cell culture plate using a Thermo Multidrop Combi (prepared in assay buffer at 6X the manufacturer’s recommended final concentration). The cell plates were then incubated at 37 °C for 30 min and then allowed to equilibrate to room temperature for an additional 30 min.

All mouse monoclonal antibodies and FAb fragments were first tested in the absence of glycine in the FLIPR assay to determine if they could activate the channel (i.e., agonist-like). Dose response plates containing a 1:2 stepwise dilution series of each antibody and FAb were prepared in low-chloride assay buffer (10 mM HEPES, 60 mM NaCl, 5 mM KCl, 2 mM MgCl_2, 1 mM CaCl_2, 10 mM D-glucose, 160 mM D-mannitol and 2 M KOH solution to adjust pH to 7.4) supplemented with 2% v/v DMSO in standard 384-well polypropylene plates. Antibodies that did not activate GlyRs on their own were then tested with EC_{10} glycine (10 μM) added to the buffer to determine if they could potentiate the EC_{10} glycine response. All full-length antibodies and FAbS were tested up to a final maximum concentration of 2 μM. The MP dye assay was carried out on FLIPR Tetra, which transferred 10 μL from the 4X dose response plate containing antibodies or FAbs (+/- EC_{10} glycine) and added it to the 30 μL volume in each well of
the cell plate containing MP Blue Dye. Fluorescence emission (510-545 nm/565-625 nm excitation/emission filter set, excitation intensity = 40 %, camera gain = 50 and an exposure time of 0.4 sec) was measured in real-time to detect changes in membrane potential. The net cell membrane potential changes upon activation of GlyR channels, and results in the increased efflux of Cl⁻ ions out of the cell down a concentration gradient and a robust increase in fluorescence signal. Fluorescence response was monitored out to 60 min to ensure that equilibrium was reached.

Antibodies that did not activate or potentiate GlyR channels within the first 60 min were subsequently exposed to EC₇₀ glycine to determine if these antibodies instead elicited the inhibition of glycine-induced channel activation. The high concentration of glycine was prepared at 5X in the Assay Buffer and the FLIPR Tetra was used to transfer 10 μL of glycine to the plate, containing cells pre-treated for 60 min with each antibody or FAb. Owing to the rapid activation of GlyR channels by added glycine, real-time fluorescence changes were carried out for an additional 2 min to capture the full response. Where indicated, blockade of channel activation by antibodies was achieved by co-dosing the small molecule GlyR inhibitor strychnine (10 μM) along with each antibody. The slower binding kinetics of antibodies relative to strychnine ensures rapid blockade of all GlyRs present under these assay conditions.

FLIPR kinetic traces were processed using an area under the curve relative to baseline (AUC - BL) algorithm, where the baseline was the first 10 sec of the measurement prior to addition of glycine to the cell plate. To examine glycine dose response curves obtained in the presence of fixed monoclonal antibody concentrations, data collected over a period of 60 min were subsequently normalized to percent of control (POC) using the maximum achievable glycine response and buffer alone as the assay range references. To determine the functional response of the antibodies, data were subsequently normalized to POC using the maximum achievable glycine response and baseline EC₅₀ glycine response.
as the range references. All POC normalized data were then plotted against log [glycine] or log [antibody], according to the experiment performed, and the data were fit to a non-linear regression 4-parameter Hill fit to determine the EC$_{50}$ from the resulting sigmoidal curve. Herein, this resulting EC$_{50}$ is defined as the qualitative potency of the antibodies under the in vitro conditions tested. All curve fitting was performed with GraphPad Prism 6 software. For responses collected at 5 and 60 minutes from the same samples, data were graphed as mean ± standard deviation (S.D.) and compared using a two-tailed, paired, two-sample equal variance t-test. All other comparisons were made using a two-tailed, unpaired, two-sample unequal variance t-test and reported as follows: $t$ (degrees of freedom) = $t$-statistic, $p$-value)

**Immunocytofluorescence (ICF).** Stable cell lines utilized for this assay included HEK293T cells over-expressing human GlyR$\alpha_3$$\beta$ or GlyR$\alpha_1$$\beta$ or GlyR-free parental control. Cells were plated at a density of 50,000/cells per well in 8-well CC2 treated chamber slides (Nunc, Lab Tek II; Sigma-Aldrich) and allowed to grow and expand for 48 hr (37°C, 5 % v/v CO$_2$ and 95 % humidity). Full-length primary mouse monoclonal antibodies (mAb 9A11, 14E3 and 19C8) were diluted (@ 2.5 $\mu$g/mL; final concentration) directly into the growth media (see details in “Generation of Stable Human GlyR Cell Lines” section above) and incubated using a standard “live” protocol for 1 hr at 4 °C to assess surface binding and selectivity profiles (while minimizing receptor internalization) and washed with cold phosphate buffer saline (PBS) prior to immediate fixation in fresh 4 % paraformaldehyde/PBS (10 min). Post-live-fixed cells were then rinsed three times in PBS, followed by a 1-hour incubation in the presence of Alexa Fluor-488/goat-anti-mouse-IgG (H+L) secondary antibody (highly cross-absorbed), (Molecular Probes; Thermo Fisher) diluted (1:500) in 5% NGS/PBS. Finally, cells were rinsed three more times in PBS and mounted in Fluoroshield media containing dapi staining dye (Sigma-Aldrich/ location), and single plane confocal images were captured on an inverted Carl Zeiss LSM 800 confocal microscope using ZenBlue software (ZEN version 2.1). All steps were performed at room temperature unless otherwise noted.
Antibody binding by fluorescence-activated cell sorting (FACS). Prior to flow cytometry-based binding experiments, HEK93T human GlyRα3β, GlyRα1β and parental (GlyR-free) cell lines were treated with 0.25 % trypsin-EDTA solution (Gibco, Waltham, MA) and washed with FACS Buffer (BD Biosciences) before addition to 6-well plates. Mouse antibodies at a final concentration of 3 μg/mL were incubated with 1x10^6 cells (per well / per condition) on ice for 1 hr, followed by washing with FACS buffer three times to reduce any non-specific binding. Subsequently, the cells were incubated with the Alexa Fluor-647 labelled anti-mouse secondary antibody (Cell Signaling Technology) on ice for 1 hr, followed by FACS Buffer washing. The collected cells were resuspended in FACS Buffer and 10 μL of 7-AAD viability dye (BD Biosciences) was added 5 min before cell analysis on a BD LSR II flow cytometer (BD Biosciences).

Surface Plasmon Resonance (SPR) binding experiments. To characterize the binding of GlyR antibodies and FAbs to purified GlyR channels, we used SPR methods described previously (Huang et al., 2015; Huang et al., 2017). Briefly, SPR spectroscopy measurements were performed on a Biacore T200 (GE Healthcare) at 25 °C using PBS pH 7.4 with 1 mM glycine as running buffer. L1 chips were pre-conditioned with three 30 sec injections of 20 mM CHAPS. Purified human GlyRα3 and GlyRα1 protein were each diluted to 30 μg/mL in PBS pH 7.4 containing 1 mM DDM and 0.1 mg/mL 1-palmitoyl-2-oleoyl-sn-glycero-3-phospho-(1′-rac-glycerol). The protein was passed over L1 chip and adsorbed onto the biosensor at a density of 300-500 Response Units (RU). Lipid solution (i.e., no GlyR) was used as the L1 chip blocking reagent and injected across all flow cells including reference cell. Using single cycle kinetics method, five sequential injections of increasing concentrations of FAb (i.e., 6.2 nM, 18.5 nM, 55.6 nM, 166.67 nM and 500 nM) were performed at a flow rate of 50 μL/min.

Association time was set to 1 min and final dissociation time to 30 min. The binding experiments were performed with 1 mM glycine in PBS pH 7.4 (agonist bound, active channel conformation), and with 1 μM strychnine in PBS pH 7.4 (antagonist bound, resting channel conformation). The raw data was
processed using Biacore T200 evaluation software (GE Healthcare) and the data kinetically fit to a 1:1 binding model which included a mass transfer limitation term. Binding experiments were performed in duplicate to calculate the mean association and dissociation rate constants ($k_{on}$ and $k_{off}$, respectively) and the equilibrium constant ($K_d$) values ($\pm$ S.D.).

**Tissue Distribution and Open Field Locomotor Activity in Rats.** All *in vivo* procedures described in this manuscript were approved by the Institutional Animal Care and Use Committee at Amgen (IACUC, Thousand Oaks, CA). To compare the brain distribution and subsequent CNS-related effects of therapeutic positive modulators of GlyRs the two strongest antibodies were chosen, described herein: mAbs 9A11 and 19C8. In brief, adult male Sprague Dawley rats (250 – 350 g, 8-12 weeks old, Charles River Laboratories, Hollister, CA) were intravenously (I.V.) dosed with 9A11 or 19C8 (10, 30 or 100 mg/kg) or a non-targeting isotype control (IgG1 or IgG2a) in 10 mM sodium acetate (9 % sucrose, pH 5.2), immediately placed into low-light open-field chambers (Kinder Scientific, San Diego, CA) and monitored for basic movements and rearing over a 30 minute observation period using an automated infrared photobeam approach. Open-field data were assessed using a one-way ANOVA to assess the overall test article treatment effect followed by Dunnett’s multiple comparison post-hoc tests (GraphPad Prism 5; GraphPad Software Inc., La Jolla, CA).

At 30 minutes post-dose, a blood sample was collected via tail vein sampling and processed to obtain serum for subsequent bioanalysis. Rats were then placed under 5 % isoflurane anesthesia to allow for a transcardiac saline perfusion followed by a craniotomy to collect whole brain samples. The perfused brain tissue was rinsed, weighed, and homogenized prior to bioanalysis. Concentrations of the antibodies in whole brain homogenate were assumed to be indicative of concentrations at the pharmacological site of action, and more definitive imaging or microdialysis studies were not conducted. Concentrations of mAbs 9A11, 19C8 or the isotype controls were measured in the resulting serum and
brain samples using an anti-mouse IgG immunoassay on the MSD platform (Meso Scale Discovery, Rockville, MD, USA). Capture and detection reagents consisted of a biotinylated anti-mouse IgG antibody and sulfo-tagged goat anti-mouse IgG1 or IgG2a antibody, respectively. Standard curves were included for all analytes in each respective matrix and utilized to extrapolate final analyte concentrations. As exploratory pharmacokinetic/tissue distribution studies with mAbs 9A11 and 19C8 demonstrated typical antibody pharmacokinetic profiles (Supplemental Figure 1) and spinal cord exposures that were equal to or greater than those observed in brain (Supplemental Figure 2), only whole brain tissue was collected from the open-field locomotor studies and used as a surrogate for both tissue types.
Results

1. Functional Characterization & Selectivity of GlyRα3 Monoclonal Antibodies

A panel of 6 full-length mouse monoclonal antibodies (mAbs) and corresponding fragment antigen binding (FAbs) antibodies generated against human GlyRα3 was evaluated in an in vitro cell-based assay to assess their ability to modulate human GlyR activity. The functional assays employed HEK293T cell lines overexpressing either homomeric or heteromeric subtypes of human GlyRs (GlyRα1, GlyRα3, GlyRα1β, GlyRα3β). A MP dye added to the cells reported on net changes in membrane potential induced by the addition of a single fixed concentration of antibody (100 nM) or high concentration of the endogenous agonist glycine (175 μM; positive control) over time. In the absence of the agonist glycine, mAbs 9A11, 19C8, and 17D2 (Fig 1a; light and dark-blue bars) were found to activate human GlyRα3β in a time-dependent manner and were also able to achieve maximal fluorescence responses comparable to those induced by high concentrations of glycine alone but in a slower time frame. For mAbs 9A11, 19C8 and 17D2, the extent of activation increased significantly over time and reached a maximal level, comparable to that induced by high concentrations of glycine alone, within 60 minutes (dark-blue bars). All antibodies tested were fully inhibited in the presence of the potent GlyR antagonist strychnine (10 μM) (Fig1A; gray bars) demonstrating the on-target activation of the channel and suggesting that antibody-mediated GlyRα3β activation is a reversible process. Conversely, mAbs 15B5, 14E3 and 17A1 showed no time-dependent activation of GlyRα3β within the 60 minute incubation period. However, subsequent addition of glycine (equal to the GlyRα3β EC₇₀ for glycine) to these cells...
revealed that these three antibodies significantly blocked the glycine-induced fluorescence response, suggesting that these mAbs are negative modulators of GlyRα3β (Fig. 1B; dark blue bars), as opposed to the first three which displayed a time-dependent agonist-like profile. The negative controls included monoclonal antibody 10E2 (an anti-GlyRα3 antibody, generated during the antibody campaign, that was able to recognize a linearized epitope and was used for Western Blotting only) and mAb 6C6 (a mouse monoclonal antibody against another non-GlyR membrane transporter, and therefore, does not recognize GlyRs). Neither of these negative controls (mAbs 10E2 and 6C6) was found to modulate the response of GlyRα3β (Fig. 1A and B).

Next, we investigated the ability of the agonist glycine to enhance positive modulation of GlyRα3β by lower affinity mAbs (mAbs 10H6 and 11F8) that showed a statistically significant activation profile in the absence of glycine (Fig. 2A). However, mAbs 10H6 and 11F8 could only achieve a partial response (75-80% of max glycine response) compared to the more active mAbs 9A11 and 19C8 over the same 60 minute period. We found that the addition of a low concentration of glycine (equal to the EC10 for each of the channels expressed) resulted in a consistent, but not statistically significant, enhancement of GlyRα3β activation by mAbs 10H6 and 11F8 at both 5 & 60 minute timepoints. Lastly, the weakest mAb tested (18F4), required both EC10 glycine and a period of 60 min to show a detectable GlyRα3β activation response. To better understand the interplay between glycine and the positive modulator antibodies on GlyRα3β, we also measured glycine potency in the presence of increasing concentrations of the most active positive modulators: mAb 9A11 & 19C8 (i.e., Schild Shift assay). We found that these antibodies increased glycine potency in both a dose- and time-dependent manner but did not modulate the efficacy of the agonist glycine (Fig. 2B and 2C).

To further assess for α subunit selectivity within the GlyR receptor family, all mAbs were tested against human GlyRα1β stably expressing HEK293T cells, the most relevant and complementary glycine
channel subtype. In the absence of the endogenous ligand glycine, mAb 19C8 was found to stimulate GlyRα1β in a time-dependent manner (*data not shown*) and in a way that was approaching near maximal fluorescence response comparable to that induced by high concentrations of glycine alone within 60 minutes of incubation (Fig. 3A; yellow bars). Interestingly, positive modulator mAbs 9A11 and 17D2 did not appear to activate GlyRα1β within the same timeframe, a significant difference from the responses observed in GlyRα3β expressing cells, suggesting that mAb 9A11 and 17D2 are highly selective for GlyRα3β over GlyRα1β under these assay conditions. Similarly, to what is shown in Figure 1, mAbs 15B5, 14E3 and 17A1 did not activate the GlyRα1β channel within the incubation period tested. To further interrogate the function and affinity of these mAbs, we examined their ability to either potentiate or block the GlyRα1β channel activation by subsequent addition of glycine (equal to the GlyRα1β EC<sub>70</sub> for glycine) (Fig. 3B, yellow bars). Upon subsequent addition of EC<sub>70</sub> glycine, mAbs 15B5, 14E3 and 17A1 blocked the resulting fluorescence response in each cell line, analogous to the GlyR antagonist strychnine (*data not shown*). There was no significant difference observed between GlyRα3β (> 50 % inhibition) and GlyRα1β (> 55 % inhibition) expressing cells for mAb 15B5. Interestingly, mAbs 14E3 and 17A1 produced significantly different responses in GlyRα3β or GlyRα1β expressing cells, but inhibited responses of both channel subtypes by 35-58 %, suggesting that they act as non-selective negative modulators of human GlyRs.

Following this initial assessment of function and selectivity, we selected the positive and negative modulator mAbs which induced the strongest responses and used the MP dye assay to determine their EC<sub>50</sub> or IC<sub>50</sub>, respectively, on the human GlyRα3β and GlyRα1β cell lines. These included: mAbs 9A11, 19C8, 17D2 (as positive modulators) and 15B5, 14E3 and 17A1 (as negative modulators). Positive modulator antibody strength was determined by measuring the fluorescence response in the absence of glycine while that of negative modulator antibody was measured upon
subsequent addition of EC70 glycine. All antibodies modulated GlyR activity in the low nM range (see Table 1). The three identified positive modulators (mAbs 9A11, 19C8 and 17D2) reached a maximal (> 90 %) activation level comparable to high concentrations of glycine (Fig. 3C) and activated with EC50S in the 5-12 nM range on the human GlyR heteropentamer cell lines (Table 1). The GlyRα3-selective positive modulators mAb 9A11 and 17D2 showed no functional activity on GlyRα1β while the non-selective mAb 19C8 activated GlyRα1β (Fig. 3C) and with a comparable EC50 of 9 nM as observed for GlyRα3β (Table 1). The three identified non-selective negative modulators reached a maximal inhibition level of 60-70% (Fig. 3D) with IC50-values in the 8-20 nM range on GlyRα3β (Table 1) and a maximal inhibition level of 55-65 % on GlyRα1β (Fig. 3D) with IC50 values in the 5-45 nM range (Table 1).

To complement the functional data and to further characterize the selectivity profiles of the monoclonal antibodies identified, we used two independent techniques to visualize and confirm the cell surface binding patterns of the strongest mAbs from each functional category: mAb9A11 – selective positive human GlyRα3 modulator; mAb19C8 – non-selective positive modulator; mAb14E3 – non-selective negative modulator of cells over-expressing human GlyRα3β or GlyRα1β. Using immunocytofluorescence, we detected cell surface labeling on both cell lines for non-selective mAbs 19C8 and 14E3, while the functionally selective mAb 9A11 labeled human GlyRα3β expressing cells only, in agreement with our functional data (Fig. 4A). In addition, the cell-surface binding of these antibodies was further examined using flow-cytometry as a complementary platform (Fig. 4B). In accordance with the previous data, mAb 9A11 was the only antibody that showed a selectivity profile of human GlyRα3β over GlyRα1β. Parental GlyR-free HEK293T cells were used as a negative control in both fluorescence-based platforms and no binding was detected (Fig. 4A and B). The immunofluorescent assays performed herein were purposefully done at 4 °C to minimize surface receptor internalization to support the characterization goal of confirming their cell surface selectivity profiles. These assays do not address the GlyR internalization potential of the antibodies. Such studies would need to be performed...
at room temperature. Together, these complementary results further support and strongly correlate with the selectivity profiles reported in the functional assay and suggest that mAb 9A11 is a selective GlyRα3β functional monoclonal antibody.

2. Biophysical Characterization of Fragmented Monoclonal Antibodies

To further understand the mechanisms underlying the selectivity and functional profile of these antibodies, we characterized the binding of mAb 9A11, 19C8 and 14E3 onto purified human GlyRα1 and α3 homopentameric ion channel proteins using surface plasmon resonance (SPR; purified heteropentamer material did not yield in sufficient amounts). Due to technical limitations in the method related to the bivalency of a full-length mAbs, all binding characterizations were completed using monovalent fragments (FAbs) of each respective antibody (9A11, 19C8 and 14E3). Therefore, we first characterized each FAb in the functional assay to determine their functional and selectivity profile as well as the activity profiles. To make direct comparisons with the channel subtypes available to us for SPR binding studies (homopentameric only), we extended the functional assay assessment of FAbs 9A11, 19C8 and 14E3 to include two additional HEK293T cell lines expressing either homopentameric human GlyRα3 or GlyRα1, each lacking the β subunit.

In the absence of the endogenous ligand glycine, FAb 9A11 triggered significantly different activating responses in cells expressing GlyRα3β or GlyRα3 when compared to GlyRα1β or GlyRα1, which were unresponsive during the 60 minute incubation period. These findings confirm that the FAb 9A11 retained the highly GlyRα3-selective activation profile of the full-length 9A11 mAb. Similar to full-length mAb 19C8, FAb 19C8 was found to stimulate all four GlyR cell lines comparably. Both reached the maximal fluorescence response (100%) analogous to that induced by high concentrations of glycine.
alone (Fig. 5). FAb 14E3 blocked the fluorescence response induced by the addition of glycine (equal to the glycine EC$_{70}$ for each respective channel), suggesting that this FAb functioned as a negative modulator of all GlyR channels. Although FAb 14E3 produced significantly different responses in cells expressing GlyR$\alpha_3(\beta)$ (61-64 % inhibition) and GlyR$\alpha_1(\beta)$ (24-37 %), the selectivity profile across all four cell lines is less robust since there is appreciable activity across all channel subtypes. Together, this characterization aligns with the corresponding functional profiles described using the full length mAbs in the same assay and highlights the alignment of the data obtained on the heteropentameric and the corresponding homomeric human cell lines. Interestingly, each full-length mAb was 3 to 5-fold more active than each corresponding FAb (Table 1). This is not necessarily surprising considering that each full-length mAb is bivalent and may be able to interact with multiple GlyR subunits at the same time. Nevertheless, the functional and selectivity profiles for all three FAbs correlate well with those observed for the full length mAbs originally tested against GlyR$\alpha_3(\beta)$ and GlyR$\alpha_1(\beta)$ (see Fig. 3 and Table 1).

After confirming that each FAb retained the functional and selectivity profiles of the full-length mAbs, we followed with the intended SPR studies on purified human GlyR$\alpha_3$ and GlyR$\alpha_1$ homopentameric ion channels to characterize the kinetic parameters ($k_{on}$; $k_{off}$) which contribute to FAb affinity ($K_d$). To probe the relationship between binding affinity and channel conformation, these studies were carried out in the presence of agonist glycine (active channel conformation) or antagonist strychnine (predominantly resting channel conformation). FAb 9A11 was found to be functional in the cell-based assays and positively modulated the activity of only GlyR$\alpha_3(\beta)$ channels. SPR binding studies found that FAb 9A11 had 30-40X higher affinity for GlyR$\alpha_3$ when compared to GlyR$\alpha_1$, consistent with the activity profile. The higher affinity for GlyR$\alpha_3$ is due primarily to a significantly slower off-rate from GlyR$\alpha_3$ relative to GlyR$\alpha_1$ (Fig 6; top row). FAb 9A11 binds the active and resting conformations of the purified GlyR$\alpha_3$ with comparable affinities but shows a 2-3-fold higher preference for the active conformation (Table 2). Interestingly, FAb 19C8 is non-selective in the functional assays but binds with
15 fold higher affinity for purified GlyRα3, which appears to be mostly due to a reduced $k_{off}$ relative to GlyRα1 (Fig. 6; middle row). When tested in the presence of glycine or strychnine, the positive modulator FAb 19C8 has a 4-6X higher affinity preference for active GlyR channel conformation (Table 2). In contrast, the negative modulator FAb 14E3 binds the resting conformation of both GlyRα channels with 80-100X higher affinity over the active channel conformation, which agrees with the inhibitory function of this FAb in cell-based assays (Fig. 6; bottom row and Table 2). In the strychnine-bound channels, this non-selective FAb appears to bind with a 15X higher affinity to purified GlyRα3, which might be caused by a reduced $k_{off}$ relative to GlyRα1. Based on the complete biophysical characterization of FAb 9A11, an affinity difference of >30 fold between two different channels may be required to reflect an in vitro selectivity profile from a functional standpoint. However, the relevance of these numbers in vivo has yet to be determined.

3. In Vivo Assessment of Tissue Distribution and Effect on General Locomotor Activity

To enable subsequent in vivo studies in rats, it was necessary to first evaluate HEK293T cells transiently expressing homomeric rat GlyRα3 and GlyRα1 using the same set of mAbs and FAbs to guide in the proper dosing range required for target engagement. Due to the transient nature of the expression of the rat channel, combined with the observation that the tool-reagents behave similarly on the homopentameric and heteropentameric channel compositions, we limited the scope of the in vivo study to GlyR homopentamers. We found that the affinities and selectivity profiles were highly consistent across species (selective activation by 9A11, rat-GlyRα3/rat-GlyRα1: 43 nM/no binding; non-selective activation by 19C8, ratGlyRα3/ratGlyRα1: 15.6 nM/47.0 nM).
In an effort to determine to impact of GlyRα-selectivity on the overall behavior in vivo, we selected an optimal pair of positive modulators from our collection: mAb 9A11 (GlyRα3 selective) and 19C8 (GlyRα3/1). Following a single I.V. administration of the selected antibodies across a dose range of 10, 30 and 100 mg/kg, the serum exposure of mAbs 9A11 or 19C8 was assessed in order to ensure both antibodies achieved similar target coverage relative to their in vitro EC50 values. A dose-dependent increase was observed across the doses- tested and resulted in similar serum exposures for 9A11, 19C8 or their respective isotype controls (isotype controls evaluated only at 100 mg/kg; Fig. 7A). Brain exposure was also comparable between mAbs 9A11 and 19C8 and accounted for approximately 0.02 – 0.05 % of the total I.V. dose with a brain/plasma ratio of 0.4 – 0.7 % (Fig.7B). Antibody concentrations in brain homogenate were assumed to be indicative of concentrations at the site of action (Chang et al., 2019). Assessment of target coverage suggests that mAbs 9A11 (GlyRα3) and 19C8 (GlyRα1/3) achieved approximately 1 – 3 fold coverage of their respective calculated in vitro rat EC50 values in brain tissue (Fig. 7C). Based on preliminary pharmacokinetic/tissue distribution studies, spinal cord target coverage for both mAbs would be expected to be equal to or greater than that observed in brain homogenate (Supplemental Fig. 2).

Each test group was monitored for basic movements and rearing from 0 – 30 minutes post-dosing. Following the I.V. administration of the GlyRα3/1 mAb 19C8, labored breathing was observed with increased severity with each escalating dose. For ethical reasons, this resulted in all the animals in the 100 mg/kg cohort being taken off-study prior to OFA analysis. Labored breathing was not observed following I.V. administration of the monoclonal GlyRα3-selective antibody 9A11 up to 100 mg/kg and no adverse effects were observed with either isotype control. In the open-field assay, the GlyRα3-selective antibody (mAb 9A11) did not significantly alter either measurement at any of the doses tested in the study (Fig. 8A). Conversely, the pan-GlyRα antibody (mAb 19C8) resulted in a statistically significant 58 % reduction in rearing counts at 10 mg/kg and a non-statistically significant reduction of 25 % at 30
mg/kg (Fig. 8B) with similar serum and brain exposure. Overall, both the presence of labored breathing and impact on rearing counts suggest that the selective profile of mAb 9A11 is favorable over that of the GlyRα3/1 mAb 19C8 within 10-100 mg/kg dose range.

Discussion

Ion channels play a critical role in modulating a variety of cellular functions making them an important target-class for drug discovery. While the majority of the efforts revolve around small molecule modalities, monoclonal antibody approaches (mAbs) have been investigated, however their therapeutic potential remains largely underexploited.

Herein, we present an approach, combining an antibody campaign with an HTS platform to identify large molecules capable of modulating the Cys-Loop family of ligand-gated ion channels. By using complementary in vitro approaches (FLIPR, ICF, FACS, and SPR), we identified and characterized selective and pan-surface binding monoclonal antibodies against the alpha subunit of GlyRs and found a strong correlation between observed cell surface binding and functional selectivity (Table 3). We further expended the characterization of selected tool antibodies to in vivo testing, by assessing their CNS penetrance, safety profiles and determined that GlyRα3-selective antibody had a larger dosing window and a lower impact on basic motor behaviors, following a single I.V. administration.

Given the general complexity and size of ion channels, it is no surprise that generating functional antibodies has shown limited therapeutic success. Some of the difficulties include structural and
technical considerations, such as limitations in expressing and purifying full-length human protein and challenges in designing biologically relevant HTS functional assays (reviewed in (Wilkinson et al., 2015)). In drug research and development, antibodies, targeting complex membrane proteins, may exhibit similar characteristics to those of small molecules, but their greater potential for selectivity, exquisite specificity, and long plasma half-life can enable optimization of highly desirable and therapeutically relevant attributes, such as affinity, potency, effector function and pharmacokinetic property (Dodd et al., 2018). It has yet to be fully understood if partial crossing of the BBB can be leveraged for such molecules, in the presence or absence of a shuttle-protein, but the recent regulatory approval of aducanumab (Aduhelm©) is evidence that some antibodies can cross BBB sufficiently. With advancements in the delivery of molecules across the BBB the extended application of therapeutic antibodies to the CNS might be achieved (reviewed in (Gosselet et al., 2021)).

It is noteworthy that most of the successful antibody campaigns, including representatives from the following ion-channel families: ligand gated ion channels, voltage-gated channels, calcium release-activated channels, and transient receptor potential channels ((Sun and Li, 2013; Wilkinson et al., 2015) and (Hutchings et al., 2019) resulted in functional target blockers, suggesting that the generation of activating antibodies is a relatively rare event and/or is under-represented in the field due to higher biological relevance of ion channel blockers. Within the aforementioned list, one will appreciate the near absence of engineered antibodies targeting members of the Cys-Loop family of ligand-gated ion channels. Indeed, glycine receptors play an important role in central signal inhibition, where positive modulation of these channels leads to neuronal silencing, thus offering a way to modulate various neurological conditions with underlying neuronal hyperexcitability symptoms. The naturally occurring antagonist-GlyRα1 antibodies reported in adult and pediatric patients suffering from progressive encephalomyelitis with rigidity and myoclonus (PERM) suggest that this target-class can be modulated by large-molecules, if present in sufficient concentration in the CNS. Moreover, the antagonist profile of
those antibodies aggravates the patients’ symptoms thus highlighting a therapeutic need for activators of the corresponding receptors and/or neuronal pathways (see reviews by (Sarva et al., 2016) and (Crisp et al., 2019). The herein described GlyR antibody campaign has given rise to GlyRα–selective monoclonal antibodies with diverse activity modulating profiles (activators and inhibitors).

We further leveraged SPR studies of purified human GlyRα3 and GlyRα1 ion channels to understand the contribution of on- and off-rates to binding affinities. A closer analysis of the SPR binding data revealed that the selective tool-antibodies showed a clear difference in binding kinetics between the two GlyRα channel subtypes. SPR binding data suggest that i) these antibodies bind to the extracellular domain of GlyRs, ii) do not occlude the orthosteric binding sites of glycine or strychnine and iii) favor either the active “open” channel conformation (19C8) or the resting “closed” channel (14E3) conformation, and that this conformational preference may be responsible for the resulting activating or inhibitory functional profiles, respectively. It is important to highlight that in our in vitro studies, the GlyRs were certainly desensitized as time-elapsed, similarly to that reported for AM-3607 (Huang et al., 2017) and that further structural studies would be required to fully-define these functional profiles. A clear limitation in our current study is the lack of electrophysiology for these tool-antibodies. In fact, the long exposure times required in the in vitro assays rendered this very difficult to assess in cultured HEK293T cells and would ultimately be best evaluated in an ex-vivo rat spinal cord slice preparation to fully leverage the local neuronal circuitry that these channels govern. This fell outside of the scope of this work and should be evaluated later.

To further expand on the therapeutic possibilities of these tools, we evaluated their capability in crossing the BBB following a single I.V. administration. The brain to serum exposure ratios (0.4 – 0.7 %; Fig. 7A and 7B) for mAbs 9A11 and 19C8 were somewhat higher than the range observed with most IgG1- or IgG2-type monoclonal antibodies (0.1 – 0.2 %), but consistent with reported values for
antibodies that engage CNS targets such as aducanumab (1.3 % in Tg2576 transgenic mice) (Sevigny et al., 2016). More importantly, the absolute brain concentrations of either antibody were sufficient to cover their respective EC50s (~1-3 fold) in brain (Fig. 7C), suggesting the ability to elicit a pharmacological or toxicological response, based on existing small molecule data (see (Huang et al., 2017) for an efficacious non-selective GlyRs small molecule in a chronic pain assay). As preliminary pharmacokinetic/tissue distribution studies demonstrated equal to or greater spinal cord exposure of each antibody relative to brain (Supplemental Fig. 2) and both mAbs are expected to have similar distribution patterns, it can be postulated that significant target coverage in the spinal cord was achieved for both antibodies in the current study considering the reported expression of GlyRα1/3 in the rodent CNS (Harvey et al., 2004). We selected mAbs 9A11 and 19C8 as ideal proof-of-concept tool molecules based on similarities in their functional attributes (activators), brain-target coverage and their dissimilarity in selectivity profile (for pain field perspective on this topic, see most recent review by (Zeilhofer et al., 2021). We set out to compare their overall safety profile and therapeutic dose-range and found that the selective antibody (mAb 9A11) had a safer overall profile when compared with the non-selective antibody (mAb 19C8) (Fig. 8). Interestingly, a similar (but less pronounced) effect was also noted on rearing (but not basic movement) in mice dosed with an efficacious (non-selective) GlyR small molecule potentiator AM-1488, with similar target coverage (Bregman et al., 2017; Huang et al., 2017), implying a possible role for GlyRα1 in the reduced locomotor activity. A noteworthy, dose-dependent increases in the severity of labored breathing were observed with mAb 19C8, supporting the role of GlyRs in regulating respiration (Schmid et al., 1991; Bonham, 1995; Liu and Wong-Riley, 2013; Ghali, 2019). These data, in combination with the results seen by (Huang et al., 2017), suggest that selectivity, while not required for efficacy, may be beneficial to alleviate limiting side effects of a potential therapeutic antibody. However, the efficacy of a GlyRα3 selective molecule has yet to be demonstrated and falls outside of the goal of this publication. Given the requirement for the 100 mg/kg dose,
necessary to achieve minimal target-coverage (as assessed by (Huang et al., 2017)), the observed side-effects would limit an ability to perform a true dose dependent efficacy study over a meaningful range of CNS target coverage. Increasing the potency of these tool antibodies or identifying another antibody with a similar selectivity profile and greater sensitivity (in pM range) would be necessary before efficacy assessment.

Together, our data demonstrate that in vitro HTS platform can be leveraged to identify a wide range of antibodies directed against Cys-Loop family of ligand-gated ion channels. In vitro, glycine receptor function can be modulated in a dose-dependent manner using high-affinity biologic tools and, despite the high protein homology between the GlyRα3 and α1 subunits, selectivity is achievable within this receptor family. In vivo, we demonstrate that the evaluated biologics can cross the rat BBB sufficiently enough to cover the therapeutic target at the concentrations up to 3-fold higher than the corresponding in vitro channel EC50 and we show, for the first time, a benefit of selectivity of GlyRα3 over GlyRα1 to a potential therapeutic molecule’s safety profile.
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Footnotes

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Figure Legends

Figure 1. *In vitro* functional characterization of anti-GlyR mouse monoclonal antibodies in the membrane potential (MP) dye FLIPR assay on human GlyRα3β expressing cell line. Antibodies were first evaluated for agonist-like activity. (A) Activation relative to the maximum achievable glycine response (175 μM glycine) was time-dependent. Three of the eight mAbs tested (9A11, 19C8, 17D2) activated human GlyRα3β in the absence of the agonist glycine within a 5 min incubation period (light blue bars). This activation was time-dependent, increasing significantly (>99.5% confidence) over a period of 60 min (*t*(5) = 14.6, *p* = .000027 for 9A11; **t*(5) = 23.5, *p* = .0000026 for 19C8; ***t*(2) = 19.7, *p* = .0026 for 17D2) (dark blue bars). By contrast, full activation achieved by high concentrations of glycine is achieved within 5 min and maintained over the course of 60 min. Activation was completely blocked in the presence of 10 μM strychnine (gray bars). (B) Non-activating GlyR antibodies were assessed for inhibitory activity by adding EC70 glycine. Monoclonal Abs 15B5, 14E3, 17A1 were confirmed inhibitors on human GlyRα3β cells. Negative controls included antibody clone 6C6, raised against a membrane transporter unrelated to GlyRs, and anti-GlyRα3 antibody clone 10E2 known to specifically recognizes a linear GlyRα3 subunit epitope and used as a Western Blot reagents for detection of denatured GlyRα3. Negative controls did not display any functional activity. Glycine alone (175 μM) was used as a positive control and its response was not time-dependent and was inhibited by strychnine (10 μM). Data represent the mean ± S.D. of data collected in ≥ 3 independent experiments.

Figure 2. Functional activation of human GlyRα3β expressing cell line by anti-GlyRα3 mouse monoclonal antibodies is enhanced by the agonist glycine. Potentiation profile of anti-GlyRα3 mAbs that failed the activation screen were further evaluated. (A) Potent anti-GlyRα3 mAbs 9A11 and 19C8 activated human GlyRα3β in the absence of the agonist glycine within a 5 min incubation period (light blue bars) and the effect increased significantly (>99.5% confidence) over a period of 60 min (*t*(5) = 14.6, *p* = .000027 for 9A11; **t*(5) = 23.5, *p* = .0000026 for 19C8) to a level comparable to the maximum achievable glycine response (175 μM glycine). While the addition of EC10 glycine did not further
enhance the response at 60 min, activation of GlyRα3β by both 9A11 and 19C8 was significantly enhanced (>99.8% confidence) at 5 min in the presence of EC10 glycine ($t^2(4)=7.5, p=0.0017$ for 9A11; $t^2(3)=13.0, p=0.00098$ for 19C8). In the absence of glycine, activation of GlyRα3β by anti-GlyRα3 mAbs 10H6 and 11F8 was minimal (<5%) after 5 min but increased significantly (>95% confidence) over a period of 60 min (**$t^2(2)=7.7, p=0.016$ for 10H6; ****$t^2(2)=6.1, p=0.025$ for 11F8) reaching ~75-80% relative to maximum glycine activation. Addition of EC10 glycine enhanced response of mAbs 10H6 and 11F8 but was not statistically significant. mAb 18F4 required both EC10 glycine and a period of 60 min to show any detectable activation response. Data represent the mean ± S.D. of data collected in ≥3 independent experiments. (B, C) GlyRα3β activator mAbs 9A11 and 19C8 enhanced the potency of the agonist glycine in dose-dependent and time-dependent manner. Both 9A11 and 19C8 mAbs were able to left-shift the glycine dose response curve within 5 min (graphs on the left) of addition to cells expressing human GlyRα3β. Comparable effects on glycine potency were achieved with ~40-fold and 20-fold lower anti-GlyRα3 mAb concentrations after 60 min, for 9A11 and 19C8, respectively (graphs on the right). All data were fit to the mean ± S.D. of responses measured in at least 3 independent experiments.

Figure 3. Selectivity and activity assessments of mean functional response of anti-GlyRα3 monoclonal antibodies on human GlyRα3β or GlyRα1β expressing cell lines. (A) Selectivity of activation was assessed following a 60 minute incubation of cells expressing human GlyRα3β (blue) or GlyRα1β (yellow) with each mAb (100 nM). Responses were compared to the maximum achievable glycine response (175 μM glycine) over the same time period. Monoclonal Abs 9A11 & 17D2 produced activation profiles that were significantly different (>99.5% confidence) between cells expressing GlyRα3β (>90%) and GlyRα1β (<5%) after 60 min (*$t^2(2)=15.4, p=0.0042$ for 9A11; ****$t^2(2)=14.4, p=0.0048$ for 19C8) and demonstrated a high degree of selectivity for GlyRα3β. Monoclonal Ab 19C8 also produced significantly different responses (>95% confidence) but demonstrated a poorer overall selectivity profile by activating both channel subtypes >70% (**$t^2(2)=5.6, p=0.030$ for 19C8). Negative controls mAb 6C6 and 10E2, had no functional activity on either cell line. (B) Selectivity of inhibition of human GlyRα3β and GlyRα1β receptors was assessed by subsequently adding EC70 glycine. There was no significant difference observed between GlyRα3β (>50% inhibition) and GlyRα1β (>55% inhibition) expressing cells for mAb 15B5. Monoclonal Abs 14E3 and 17A1 produced significantly different (>99% confidence) responses between cell lines while displaying preferential inhibition of GlyRα3β (*$t^4(4)=7.9, p=0.0014$ for 14E3; **$t^2(2)=11.6, p=0.0074$ for 17A1). Monoclonal Abs 14E3 and 17A1 demonstrated poor overall selectivity by inhibiting both GlyRα3β and GlyRα1β >35%. (C) Dose response activation curves for mAb 9A11, 19C8, 17D2, 15B5, 14E3 and 17A1 were obtained after a 60 minute incubation in the absence of glycine with cells expressing human GlyRα3β (left panel in blues) or GlyRα1β (right panel in yellows). (D) Dose response inhibition curves were obtained in the presence of EC70 glycine with cells expressing human GlyRα3β (left panel in blues) or GlyRα1β (right panel in yellows). All data were fit to the mean ± S.D. of responses measured in at least 3 independent dose-response experiments.
(B). (A) Representative photomicrographs using GlyRα3 mAb 9A11 and 14E3 & 19C8 in live cells confirmed that mAb 9A11 selectively recognized cells expressing human GlyRα3β, while mAbs 14E3 & 19C8 recognized both GlyRα3β and GlyRα1β cell lines. Parental HEK293T cells were used as a negative control and were not labeled by any of the mAbs tested herein. (B) Representative FACS traces of live HEK293T cells used in the ICF study further confirmed the same cell surface binding patterns. (Scale bar = 10 μm)

Figure 5. Characterization of mean functional response of FAbs generated from mAb 9A11, 19C8 and 14E3 on human GlyRα3β or GlyRα1β cell lines. Activation of GlyRα3β (blues) and GlyRα1β (yellows) expressing cells was assessed relative to the maximum achievable glycine response (175 μM glycine) after 60 min incubation with 100 nM fixed concentration of each FAb. FAb 9A11 produced activation profiles that were significantly different (>99.9% confidence) between cells expressing GlyRα3β (75-85%) and GlyRα1β (< 5%) after 60 min (*t(4) = 29.8, p = 0.000075 for GlyRα3β vs GlyRα1β; **t(2) = 7.5, p = .017 for for GlyRα3 vs GlyRα1) and demonstrate a high degree of selectivity for GlyRα3β channels, which is consistent with the FLIPR and ICF/FACS data. FAb 19C8 was non-selective and positively modulated all tested GlyR channels similarly. Inhibition by non-activating FAbs was further assessed by adding EC70 glycine. The FAb 14E3 produced significantly different (>95% confidence) responses between cell lines while displaying preferential inhibition of GlyRα3β (****t(6) = 6.4, p = .00068 for GlyRα3β vs GlyRα1β; ****t(2) = 5.2, p = .035 for GlyRα3 vs GlyRα1). FAb 14E3 demonstrated poor overall selectivity by inhibiting all GlyRα3β and GlyRα1β subtypes >25%. FAb 14E3 inhibited all channels and displayed an apparent preference for negative modulation of GlyRα3β over that of GlyRα1β. Data represent the mean ± S.D. of data collected in ≥ 3 independent experiments.

Figure 6. Representative SPR binding kinetic traces for the binding of FAbs 9A11, 19C8 and 14E3 to purified human GlyRα3 & GlyRα1 channel protein. All FAbs were tested in the presence of 1 mM glycine or 1 μM strychnine to induce the active or resting conformation of the GlyR channels, respectively. FAb 14E3 bound with highest affinity to the resting channel conformation, while FAb 19C8 bound with highest affinity to the active channel conformation. Black traces reflect the observed binding data from sequential injections of increasing concentrations of FAb (6.2nM, 18.5nM, 55.6nM, 166.67nM and 500nM). Red traces reflect a data fit to a 1:1 binding model. FAb 9A11 bound with comparable affinities to both channel conformations. All three FAbs showed varying preferences for GlyRα3 in the SPR binding assay due to slower dissociation rates from that channel. FAb 9A11 was the most α3-selective FAb in our collection.

Figure 7. Dose range finding serum and brain exposure of mAbs 9A11 and 19C8 and corresponding isotype controls following a single intravenous (I.V.) administration in adult male Sprague-Dawley rats. Serum (A) and brain (B) exposures to mAbs 9A11 (selective agonist; blue) and 19C8 (pan-GlyR agonist; green) assessed 30 minutes post-dose exhibited a classic dose-dependent increase comparable to the exposure of the isotype control antibodies at 100 mg/kg. The dotted lines represent the corresponding rat (r) GlyRα3 (blue) or GlyRα1 (yellow) channel in vitro EC50 values. (C) The resulting brain exposures were of sufficient magnitude to cover by 1 – 3-fold their respective measured rat GlyRα3 (blue) and/or GlyRα1 (yellow) in vitro EC50 values in the 100 mg/kg dose group.
Figure 8. Open field assessment dose-response of mAbs 9A11 and 19C8 following a single intravenous (I.V.) administration in adult male Sprague-Dawley rats. The effects of dosing male Sprague-Dawley rats with mAbs 9A11 (selective agonist; blue) or 19C8 (pan-GlyRα3/1 agonist; green) on general locomotor activity was assessed by unbiased-electronic scoring of total basic movement and total rearing. (A) The GlyRα3-selective mAb 9A11 (blue) did not result in statistically significant changes to either total rearing counts or basic movement over a 30 minute period following I.V. dosing ranging from 10 – 100 mg/kg. (B) A 58% reduction in total rearing counts (* p < 0.05, Dunnett’s MCT) was observed following a 10 mg/kg I.V. administration of the pan-GlyRα3/1 mAb 19C8 (green). More importantly, all animals in the 100 mg/kg mAb 19C8 test group were taken off-study prior to open-field assessment due to general health observations (labored breathing).

Tables

Table 1. Correlation of FLIPR assay functional response for full-length (mAb) and fragmented (FAb) mouse monoclonal antibodies on various cell lines stably expressing human GlyR channels.

<table>
<thead>
<tr>
<th>mAb</th>
<th>Full-length Abs Activity EC₅₀ (nM)</th>
<th>FAbs Activity EC₅₀ (nM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GlyRα3β</td>
<td>GlyRα1β</td>
</tr>
<tr>
<td>14E3</td>
<td>8.1</td>
<td>11.2</td>
</tr>
<tr>
<td>15B5</td>
<td>11.2</td>
<td>4.9</td>
</tr>
<tr>
<td>17A1</td>
<td>18.1</td>
<td>42.3</td>
</tr>
<tr>
<td>19C8</td>
<td>6.1</td>
<td>8.9</td>
</tr>
<tr>
<td>9A11</td>
<td>5.3</td>
<td>nd</td>
</tr>
<tr>
<td>17D2</td>
<td>11.9</td>
<td>nd</td>
</tr>
</tbody>
</table>
Table 2. Summary of SPR binding kinetic data to purified homopentameric human GlyRα receptors

<table>
<thead>
<tr>
<th>FAb</th>
<th>Condition</th>
<th>GlyRα3</th>
<th>GlyRα1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>kₘₐₓ (M⁻¹s⁻¹)</td>
<td>kₐₚ (s⁻¹)</td>
</tr>
<tr>
<td>14E3</td>
<td>+ glycine</td>
<td>5 ± 3 x10⁵</td>
<td>3 ± 2 x10⁻²</td>
</tr>
<tr>
<td></td>
<td>+ strychnine</td>
<td>10 ± 2 x10⁵</td>
<td>&lt; 1 x10⁻⁵</td>
</tr>
<tr>
<td>19C8</td>
<td>+ glycine</td>
<td>1.6 ± 0.5 x10⁵</td>
<td>7 ± 3 x10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>+ strychnine</td>
<td>6 ± 2 x10⁴</td>
<td>1.8 ± 0.5 x10⁻³</td>
</tr>
<tr>
<td>9A11</td>
<td>+ glycine</td>
<td>1.9 ± 0.4 x10⁵</td>
<td>7 ± 2 x10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>+ strychnine</td>
<td>1.0 ± 0.3 x10⁵</td>
<td>8 ± 5 x10⁻⁴</td>
</tr>
</tbody>
</table>

Note: Values represent mean ± S.D. of at least 2 independent SPR experiments

Table 3. Correlation of FLIPR assay functional response with cellular binding determined by immunocytofluorescence against human GlyR expressing cell lines
<table>
<thead>
<tr>
<th>mAb</th>
<th>Immunocytofluorescence</th>
<th>Functional Profile</th>
<th>Selectivity Profile on GlyRs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GlyRα3β</td>
<td>GlyRα1β</td>
<td>GlyRα3β</td>
</tr>
<tr>
<td>14E3</td>
<td>++</td>
<td>++</td>
<td>Inhib.</td>
</tr>
<tr>
<td>15B2</td>
<td>++</td>
<td>++</td>
<td>Inhib.</td>
</tr>
<tr>
<td>17A1</td>
<td>++</td>
<td>++</td>
<td>Inhib.</td>
</tr>
<tr>
<td>19C8</td>
<td>++</td>
<td>++</td>
<td>Activ.</td>
</tr>
<tr>
<td>9A11</td>
<td>++</td>
<td>NB</td>
<td>Activ.</td>
</tr>
<tr>
<td>17D2</td>
<td>++</td>
<td>NB</td>
<td>Activ.</td>
</tr>
<tr>
<td>6C6</td>
<td>NB</td>
<td>NB</td>
<td>None</td>
</tr>
<tr>
<td>10E2</td>
<td>NB</td>
<td>NB</td>
<td>None</td>
</tr>
</tbody>
</table>

Note: NB = no binding detected
Figure 2

A. Graph showing % Activation (rel. to max) for different cell types and time points.

B. Graphs showing POC (rel. to max) for mAb9A11 at 5 min and 60 min, with various concentrations of glycine.

C. Graphs showing POC (rel. to max) for mAb19C8 at 5 min and 60 min, with various concentrations of glycine.
Figure 4

A.  

<table>
<thead>
<tr>
<th></th>
<th>GlyRα3β</th>
<th>GlyRα1β</th>
<th>Parental</th>
</tr>
</thead>
<tbody>
<tr>
<td>mAb9A11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mAb19C8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mAb14E3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

B.  

FACS

Legend: - Parental (no)  - Parental (IF)  - GlyRα3β  - GlyRα1β

Count

-10^1 to 10^5
Figure 6

GlyRα3

GlyRα1

FAB 9A11
(+ glycine)

FAB 19C8
(+ glycine)

FAB 14E3
(+ strychnine)

Response Units (RU)

Time (s)
Figure 7

A. Serum Exposure

B. Brain Exposure

C. CNS Target Coverage
Modulation of ligand-gated glycine receptors via functional monoclonal antibodies

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Supplemental Figure 1

Serum exposure of mAb 9A11 (● and ■) and mAb 19C8 (▲ and ▼) following intravenous administration in male rats. Male Sprague Dawley rats (n = 3/group, 250 – 350 g, 8-12 weeks old, Charles River Laboratories, Hollister, CA) were intravenously administered 9A11 or 19C8 at a dose of 10 mg/kg. Blood samples were collected via jugular vein catheters from conscious animals and maintained at room temperature for approximately 30 minutes to allow for clotting prior to centrifugation to obtain serum for analysis. GlyRα antibodies were captured with an anti-mouse IgG antibody (9A11, ●; 19C8, ▲) or with purified recombinant human GlyRα3 protein (9A11, ■; 19C8, ▼) and detected with subtype specific antibodies. Both antibodies displayed expected pharmacokinetic profiles in male rats with no evidence of catabolic clipping based on the similar profiles observed using the two different antibody detection methods.
Supplemental Figure 2.

Spinal cord and brain exposure of mAb 9A11 (●) and mAb 19C8 (●) following 10 mg/kg intravenous administration in male rats. Male rats were dosed as described in Supplemental Figure 1. Immediately following blood collection at 24, 96 or 168 hours post dose, animals were asphyxiated via CO₂ exposure and perfused prior to whole brain and spinal cord (cervical, thoracic and lumbar) extraction in vertebral segments. Tissues were rinsed in 0.9% saline and weighed prior to homogenization and analysis as described in the Methods. Spinal cord concentrations of each antibody were approximately equal to (for 19C8) or greater than (for 9A11) brain concentrations at each sampling time point. Rat GlyRα1 or GlyRα3 EC50 values are shown on each plot for reference. Based on these results, subsequent in vivo studies (main manuscript Figures 7 and 8) utilized intravenous doses of 10, 30 and 100 mg/kg.