The role of loops B and C in determining the potentiation of GABAA receptors by midazolam

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Abstract

Many benzodiazepines are positive allosteric modulators (PAMs) of GABA\(_A\) receptors that cause sedation, hypnosis, and anxiolysis. Benzodiazepines bind GABA\(_A\) receptors at the extracellular interface of the \(\alpha\) and \(\gamma\) subunits. Within the \(\alpha\) subunit, the benzodiazepine binding site is defined by three highly conserved structural loops, loops A-C. Although previous mutagenesis studies have identified His102 in loop A as important for benzodiazepine modulation of GABA\(_A\) receptors, the functional roles of many of the other conserved residues in loops A-C remain incompletely understood. In this study, we made single mutations in loops A-C of the benzodiazepine binding site across all six \(\alpha\) subunits. We used whole-cell patch clamp recording to measure the functional effects of these mutations on midazolam potentiation. The results showed that mutating the threonine in loop B and serine in loop C (Thr163 and S206 in human \(\alpha_1\)) did not abolish the receptors’ responsiveness to midazolam, as the \(\alpha_1(H102R)\) mutation did. The loop C mutations exhibited a novel array of \(\alpha\)-isoform specific effects on midazolam potentiation. The \(\alpha_3(S230I)\) and \(\alpha_5(S209I)\) mutations had the largest effect on midazolam potentiation, increasing the efficacy of midazolam. Novel benzodiazepines targeting loop C may represent a future direction for designing new drugs that specifically alter the activity of \(\alpha_3\) and \(\alpha_5\)-containing GABA\(_A\) receptors.

KEYWORDS

allosteric modulator, benzodiazepine, canonical loops, GABA(A) receptor

1 | INTRODUCTION

Benzodiazepines can induce sedation, anxiolysis, amnesia, seizure reduction, and muscle relaxation by enhancing inhibitory GABAergic neurotransmission through the \(\gamma\)-aminobutyric acid type A (GABA\(_A\)) receptors.\(^1,2\) GABA\(_A\) receptors are cys loop ligand-gated ion channels assembled from five subunits \((\alpha 1-6, \beta 1-3, \gamma 1-3, \delta, \varepsilon, \theta, \pi, \rho 1-3)\) around a central pore.\(^3\) GABA\(_A\) receptors have a stoichiometry of two \(\alpha\) subunits, two \(\beta\) subunits and one auxiliary subunit (predominantly \(\gamma\) or \(\delta\)) (Figure 1A). Each subunit has a different spatial, temporal and pharmacological profile in the brain.\(^4,5\) Upon GABA binding, the receptor's anion channel opens, causing hyperpolarizing...
membrane potentials in the adult mammalian brain. One highly relevant class of positive allosteric modulators (PAMs) of GABA_A receptors are benzodiazepines.

Benzodiazepines bind at the extracellular interface of the α and γ subunits. There are three structural loops (loops A, B, and C) on the α-subunit and three loops on the γ2 subunit (loops D, E, and F) that form the structure of the benzodiazepine binding site (Figure 1B). Loops A-C form connectors between sequential β-strands. They are sometimes referred to as loop 5 (loop A), loop 8 (loop B) and loop 10 (loop C), based on nomenclature for the acetylcholine receptor. Loops A-C are highly conserved across GABA_A receptor subunits and form a homologous GABA agonist binding site at the β+γ/α interface.7,10

A combination of mutagenesis with functional or binding assays has been used to determine the role of specific amino acids within the structural loops A-F of the benzodiazepine site.11-16 The conserved histidine in loop A (His101 in rodents and His102 in bovine and human cDNAs) is important for the molecular and behavioral actions of diazepam using in vitro experiments6,11 and knock-in mice.2,17 Other residues in loops A-C have been studied, but most mutagenesis experiments were constrained to mutating less than three α subunit isoforms. This limits the conclusions drawn. Many benzodiazepine ligands bind to multiple GABA_A receptor assemblies, and a mutagenesis study across the six α subunits is needed to determine the structural role of specific residues on benzodiazepine efficacy and potency.

In this study, we examined two residues within the conserved loops B and C across all six α subunits. The conserved threonine in loop B (GSYAYTR) and serine in loop C (SSSTGEYV) have been reported to differentially affect the potency and efficacy of benzodiazepines across the six human α subunits. In this study, we mutated the highly conserved histidine in loop A (His102 in α1), threonine in loop B (Thr163 in α1), and serine in loop C (Ser206 in α1) in all six GABA_A α subunits. The α4 and α6 subunits have different residues (R100, P161, and I/N204) in these locations (Figure 1C) and form GABA_A receptors insensitive to classic benzodiazepines, historically known as diazepam-insensitive receptors.22 If midazolam acts as a canonical benzodiazepine then canonical mutations in α1-3 and α5 to residues present in α4 and α6 should block its actions and vice versa in α4 and α6. Whole-cell patch clamp recording was used to measure the actions of midazolam on mutated α6β2γ2z GABA_A receptors. Midazolam was selected for this study because it is commonly used in the clinic to induce sedation,23 it is easier to handle than other benzodiazepines (lower affinity for diazepam-sensitive receptors and higher solubility), and knowledge of its pharmacology could provide insight into designing novel sedatives with fewer side effects. We found that mutating the threonine and serine in loop B and loop C altered the efficacy of midazolam less than mutating the histidine in loop A across α1-6. Surprisingly, mutating the serine in loop C altered

<table>
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<tr>
<th>Subunit</th>
<th>Loop A</th>
<th>Loop B</th>
<th>Loop C</th>
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**FIGURE 1** The structural loops A-C within the α subunit form the benzodiazepine binding site on the GABA_A receptor. (A) The assembly of the α6β2γ2z GABA_A receptor with arrows pointing to the two GABA sites (black) and high-affinity benzodiazepine site (red). (B) The structural loops A-C (blue, magenta, cyan) on the α subunit and loops D-F (grey) on the γ subunit form the benzodiazepine site (red dotted circle) on the α6β2γ2z receptor. Target residues used in this study noted under loops. (C) The structural loops A-C are highly conserved across GABA_A receptor α subunits. The location of the residues of interest are highlighted in bold with the specific mutation numbers listed to the right. The numbering is based on the human mature peptide sequences not including the signal peptide (peptide sequences based on NP_000797 (α1), NP_000798 (α2), NP_000799 (α3), NP_000800 (α4), NP_000801 (α5), NP_000802 (α6)). The mutations made in this study are referred to by the abbreviations “loop A”, “loop B” and “loop C” in subsequent figures and text.
the efficacy of midazolam potentiation in different directions depending on the α isoform. These subunit-selective observations will be useful for the design of α3- and α5-selective benzodiazepines.

2 | MATERIALS AND METHODS

2.1 | cDNA plasmids and mutagenesis

Human (Homo sapiens) GABA<sub>A</sub> subunits (α1-6, β2, γ2s) were subcloned into pcDNA3.1+ vectors with a cytomegalovirus (CMV) promoter. The hβ2 and hα3 sequences were humanized rat (Rattus norvegicus) cDNA with amino acid substitutions made to match the human protein sequence. The α1-3, α5, β2, and γ2s subunits were a generous gift from Neil L. Harrison (Columbia University Medical Center, NY). The α4 subunit was obtained from GenScript (Piscataway, NJ), and the α6 subunit was a generous gift from Robert L. McDonald (Vanderbilt University, TN). All point mutations (listed in Figure 1C) were introduced using the QuikChange Lightening site-directed mutagenesis kit (Agilent Technologies, Santa Clara, CA) according to the manufacturer’s instructions and were confirmed by sequencing (Eurofins MWG Operon, Louisville, KY).

2.2 | Cell culture and transfection

Human embryonic kidney cells containing the SV40 T-antigen (HEK293T) were acquired from American Type Culture Collection (ATCC<sup>®</sup>, Manassas, VA), catalogue number, CRL3216. HEK293T cells were maintained at 37°C and 5% CO₂ in Eagle Minimum Essential Medium (MEM) supplemented with 5% fetal bovine serum (Atlanta Biologicals Inc., Flowery Branch, GA), 40 μM l-glutamine, 100 U/mL penicillin and 0.1 mM streptomycin. Cells were passaged regularly when they reached 70% confluency using trypsin. Cells were not passaged more than 22 times. New cells were revived from frozen stocks at passage 2.4. Cells used for in vitro electrophysiology experiments were grown on poly-D-lysine-coated glass coverslips (No.2, VWR, Radnor, PA) and transfected with X-tremeGENE (Roche Diagnostics, Indianapolis, IN) with the desired receptor subunit cDNAs at a 1:1:1 ratio to express α<sub>β2γ2s</sub> receptors (2 μg total cDNA) and with 0.5 μg green fluorescent protein (GFP) as an expression marker. The γ2s incorporation into receptors was tested with zinc inhibition assays regularly.<sup>24</sup>

Patch clamp experiments were performed on cells at 24-72 hours post-transfection. All experiments were performed at 22°C. Experiments consisted of at least five cells recorded per day from at least two transfections across 3-4 days to control for cell health and transfection efficiency. At least three cells expressing wild-type receptors were recorded on days that mutant receptors were tested to provide a time-matched expression control. All reagents were purchased from Sigma-Aldrich (St. Louis, MO) unless otherwise stated.

2.3 | In vitro electrophysiology

Wildtype and mutant GABA<sub>A</sub> receptors were characterized using whole-cell voltage-clamp electrophysiology of HEK293T cells expressing α<sub>β2γ2s</sub> receptors and GFP, similar to methods previously described.<sup>25</sup> Patch pipettes were created from thin-walled borosilicate glass (TW150F-4, World Precision Instruments, Inc., Sarasota, FL) using a horizontal puller (P97, Sutter Instruments, Inc., Novato, CA) to give a resistance of 2-8 MΩ when filled with intracellular solution (120 mM KCl, 2 mM MgCl₂, 10 mM EGTA, 10 mM HEPES, and adjusted to pH 7.2 with NaOH, 315 mOsM). Extracellular solution contained 161 mM NaCl, 3 mM KCl, 1 mM MgCl₂, 1.5 mM CaCl₂, 10 mM HEPES, and 6 mM D-glucose, adjusted to pH 7.4 with NaOH (320-330 mOsM). GABA and midazolam (Hospira, Lake Forest, IL) were delivered using a rapid solution changer (RSC-160, BioLogics Science Instruments, Seyssinet-Pariset, France) connected to a 10-channel infusion pump (KD Scientific Inc., Holliston, MA). The perfusion system was controlled by protocols written in pClamp 9 (Molecular Devices, LLC, Sunnyvale, CA). Whole-cell currents were recorded at -60 mV, filtered at 100 Hz and sampled at 200 Hz with a MultiClamp 700B amplifier (Molecular Devices, LLC) and DigiData 1322A (Molecular Devices, LLC) digitizer. GABA concentration-response assays were performed by exposing each whole-cell patch to eight concentrations of GABA spread over a 3.5 logarithmic decade. Each GABA exposure was for 2 seconds with 8 seconds of washout between ligand application. GABA concentrations for α<sub>β2γ2s</sub> receptors were: 0.3-1000 μM (α1), 0.1-300 μM (α2 & α3), 0.03-100 μM (α4), and 0.01-30 μM (α5 & α6). Midazolam concentration-response assays were performed by exposing patches to two successive EC<sub>10</sub> (10% effective concentration) GABA exposures and then exposing the patches to ascending concentrations of coapplied midazolam (10, 50, 100, 500, 1000 nM) and GABA (EC<sub>10</sub>) (See Figure S1). Each midazolam drug exposure consisted of 3 seconds of coapplied GABA + midazolam and then 2 seconds of GABA at the end of each midazolam exposure before 5 seconds of washout in extracellular solution (see Figure S1 for waveform of drug exposure). GABA pre- and postcontrol runs were performed before and after each midazolam assay for each cell to verify a consistent EC<sub>10</sub> GABA response and full washout of midazolam. Control runs consisted of 3 seconds of GABA (EC<sub>10</sub>) and then 3 seconds of a saturating GABA concentration (100-300 μM depending on the α subunit) with 8 seconds of washout between ligand applications. Cells were recorded with the midazolam protocol no more than two times to avoid desensitization and incomplete washout or irreversible modulation.

2.4 | Whole-cell analysis

Recordings were analyzed using MATLAB (Math Works, Inc., Natick, MA). GABA concentration-response relationship: Whole-cell peak currents (I) were measured from GABA concentration-response assays and fit using a nonlinear regression analysis based on the Hill equation: $I = I_{max}[A]^{nH}/[EC_{50}^{nH} + [A]^{nH}]$ where $I$ is the peak current amplitude, $I_{max}$ was maximum current amplitude, $EC_{50}$ was the half-maximal GABA concentration, $A$ was the agonist concentration, and $nH$ was the Hill coefficient. The maximum peak current, $EC_{50}$ and Hill coefficient were estimated for assays from each cell. When Hill parameters are estimated from whole-cell recordings, the changes in...
the parameters across receptor conditions can be ascribed to the following changes in receptor physiology. Changes in maximum current can be due to changes in the single-channel conductance or the rate of desensitization. Changes in cell surface receptor expression can cause minor changes in maximum current, but are unlikely to occur in the time course of our experimental protocol. Changes in the Hill coefficient can be due to changes in altered GABA cooperativity, the loss of a GABA binding site or altered channel desensitization. More often minor changes in the Hill coefficient are attributed to the altered homogeneity in the receptor population expressed by the HEK293T cell. For example, a shallower Hill coefficient could be caused by a shift in the population of receptors from mostly αβγ receptors to a combination of both αβ and αβγ receptors. Changes in GABA apparent-affinity can be due changes in GABA’s binding affinity, gating or both for the receptor. Other explanations than the above are possible but less likely, Midazolam concentration-response curves: The midazolam potentiation (%) of each GABA-evoked response was calculated by the equation: Pot = (l<sub>MDZ</sub> − l<sub>0</sub>) / l<sub>0</sub> × 100%, where Pot was potentiation (%), l<sub>0</sub> was the average amplitude of peak currents from the two EC<sub>10</sub> GABA responses, and l<sub>MDZ</sub> was the amplitude of peak currents from co-applied GABA + midazolam. The potentiation measurements from midazolam concentration-response curves were fit using the Hill equation: P = P<sub>max</sub> [M]<sup>Hill</sup> / (EC<sub>Hill</sub> + [M]<sup>Hill</sup>), where P was potentiation, P<sub>max</sub> was maximum potentiation, EC<sub>Hill</sub> was the midazolam concentration producing the half-maximal potentiation response, M was midazolam concentration, and nH was the Hill coefficient. Concentration-response relationships that were not described by a sigmoidal function were not included in our analysis (eg: no response or a linear nonsaturating response). The Hill equation was fit to each individual cell’s concentration-response curve data.

2.5 | Statistics

Optimal sample sizes (n ≥ 10 cells) were calculated beforehand from preliminary α1 mutant data using G*Power (Heinrich-Heine-Universität Düsseldorf, Germany) (α = 0.05 and β = 0.8) for a one-way analysis of variance (ANOVA) test. Hill parameters (maximum response or potentiation, Hill coefficient, EC<sub>Hill</sub>) from concentration-response curves (GABA and midazolam each) were compared for significant differences within each α subunit (α-6) and its loops A-C mutants using a one-way ANOVA at the significance threshold of α = 0.05. Where the results of the ANOVA were significant (P < 0.05), Dunnett’s post-hoc analysis for multiple comparisons (α = 0.05) was performed. Statistical analysis was carried out using Prism 7.0 (Graphpad Software, Inc., La Jolla, CA).

3 | RESULTS

We hypothesized that mutating single residues in the conserved loops A-C of the benzodiazepine binding site (Figure 1C) would alter the modulation of GABA<sub>A</sub> receptors by midazolam. Whole-cell patch clamp recording of α1-6-containing α<sub>4</sub>β<sub>2</sub>γ<sub>2</sub> GABA<sub>A</sub> receptors was used to measure the degree of potentiation by midazolam within the therapeutically relevant range of 10-1000 nM. Midazolam potentiation was measured as the percent of enhancement in GABA-evoked currents. A 100% potentiation was a doubling in amplitude of the whole-cell current relative to the control EC<sub>50</sub> GABA-response. Interestingly, we found that loop C mutations in α3 and α5 GABA<sub>A</sub> subunits increased the maximum potentiation by midazolam. However, single residue mutations in loop B and loop C did not alter, abolish or confer midazolam sensitivity as dramatically as the histidine-to-arginine exchanges in loop A.

3.1 | Loop A mutations

The loop A mutation substituted the highly conserved histidine residue for an arginine residue (FFHNG) in the α1, α2, α3, and α5 subunits. For the α4 and α6 subunits, the reverse arginine-to-histidine mutation was made. GABA concentration-response assays revealed only modest changes in loop A mutant receptors (Figure 2, Table S1). The presence of the arginine right-shifted the GABA concentration-response curves for α5(H105R) and α2(H101R)-containing receptors. This caused a threefold increase in the GABA EC<sub>50</sub> for α5(H105R) mutant receptors (α<sub>5</sub>(H105R))<sub>2</sub> = 9.84 ± 3.29 μM (n = 10); α<sub>5</sub>β<sub>2</sub>γ<sub>2</sub> = 3.18 ± 0.71 μM (n = 10), P = 0.0093) and twofold increase in the GABA EC<sub>50</sub> for the α2(H101R) mutant receptors (α<sub>2</sub>(H101R))<sub>2</sub> = 16.25 ± 2.20 μM (n = 11); α<sub>2</sub>β<sub>2</sub>γ<sub>2</sub> = 8.29 ± 0.78 μM (n = 40), P = 0.0003). Midazolam assays showed that the α1 (H102R), α2(H102R), α3(H126R), α5(H105R) mutations abolished the ability of receptors to respond to midazolam potentiation, and Hill fits could not be performed on this data (Table 1, see Table S2 for midazolam potentiation values). This is consistent with previous reports using diazepam. The α4(R100H) and α6(R100H) mutations conferred the ability to receptors to respond to midazolam potentiation (midazolam EC<sub>50</sub> α<sub>2</sub>(R100H))<sub>2</sub> = 73.99 ± 3.44 nM (n = 8) and α<sub>4</sub>(R100H))<sub>2</sub> = 41.88 ± 6.02 nM (n = 7), Figure 3C). The wildtype α<sub>4</sub>β<sub>2</sub>γ<sub>2</sub> and α<sub>6</sub>β<sub>2</sub>γ<sub>2</sub> receptors showed no notable midazolam potentiation, and no meaningful Hill parameters could be estimated (Figure 3A-B, see Table S2 for values). Confirming the role of this histidine in loop A with midazolam provided a reference for how altering a key structural residue in a conserved region of the benzodiazepine binding site can maximally alter the amplitude of midazolam potentiation of the α<sub>4</sub>β<sub>2</sub>γ<sub>2</sub> GABA<sub>A</sub> receptors.

3.2 | Loop B mutations

The loop B mutations consisted of mutating a threonine-to-proline (G59YATR) in α1-3, which we predicted would reduce the receptor’s responsiveness to midazolam. The opposite mutation (proline-to-threonine) was made in the α4-6 subunits. No significant (P < 0.05) shifts in GABA apparent-affinity were seen for any α1-6 loop B mutations (Figure 2, Table S1). The only significant (P < 0.05) changes in GABA activation were modest changes in the amplitude of the maximum whole-cell current evoked by GABA for α1(T163P),
Mutations in loops A-C across the α1-6 subunits generally had only subtle effects on the GABA concentration-response curves. (A) Example traces for wildtype α1-6-containing receptors were measured using whole-cell patch clamp recording of HEK293T cells expressing α1β2γ2 receptors. GABA concentrations (black bars) were: α1 = 0.3–1000 μM, α2 & α3 = 0.1–300 μM, α4 = 0.03–100 μM, and α5 & α6 = 0.01–30 μM. Scale bars: 5 seconds, 500 pA. (B) GABA concentration-response curves of wildtype vs mutated receptors for each of the α subunits. Line colors: wildtype (black), loop A mutation (red), loop B mutation (green), loop C mutation (blue). Loop A mutations are α1(H102R), α2(H101R), α3(H126R), α4(R100H), α5(H105R), and α6(R100H). Loop B mutations are α1(T163P), α2(T162P), α3(T187P), α4(P161T), α5(P166T), α6(P161T). Loop C mutations are α1(S206I), α2(S205I), α3(S230I), α4(I204S), α5(S209I), and α6(N204I). Insets within each subplot are example responses from the 4th and 8th GABA concentration exposures measured for wildtype receptors (black) and one selected loop mutation (in blue). Subplot GABA concentrations: α1 (10 μM and 1000 μM), α2 (3 μM and 300 μM), α3 (3 μM and 300 μM), α4 (1 μM and 100 μM), α5 (0.3 μM and 30 μM), α6 (0.3 μM and 30 μM). Scale bars are 5 sec, 500 pA. Sample sizes (cells per group) are: α1 (10), α2 (9-40), α3 (11-16), α4 (12-14), α5 (10-12), and α6 (7-15). Points are mean ± SEM and where SEM is smaller than symbols, it is not visible.
wildtype receptors ($P > 0.05$, Table 1). Only $\alpha_1(\text{T163P})\beta_2\gamma_2$ receptors had a significantly lower maximum potentiation compared to wildtype $\alpha_1\beta_2\gamma_2$ receptors ($\alpha_1(\text{T163P})\beta_2\gamma_2$: 133.8 ± 19.51%, $n = 11$; $\alpha_1\beta_2\gamma_2$: 203.0 ± 17.6%, $n = 7$, $P = 0.0092$). The $\alpha_2(\text{P166T})$ mutation produced little change in midazolam potentiation, either maximum potentiation or midazolam EC$_{50}$ ($P > 0.05$, $n = 7$ per group). The presence of a threonine residue failed to confer midazolam responsiveness to $\alpha_2(\text{P161T})\beta_2\gamma_2$ and $\alpha_4(\text{P161T})\beta_2\gamma_2$ receptors (Figure 3C, potentiation values in Table S2). Overall, the presence of a proline in this location caused only subtle changes in both GABA-activation and midazolam potentiation.

### 3.3 | Loop C mutations

The loop C mutations (SSTGHEYV) had little effect on GABA apparent-affinity but more noticeable effects on the magnitude of the midazolam potentiation of $\alpha_4\beta_2\gamma_2$ GABA$_A$ receptors. Five of the six loop C mutations failed to significantly ($P > 0.05$) alter the receptor apparent-affinity for GABA, Table S1). The exception was $\alpha_6(\text{N204I})$ (EC$_{50}$: $\alpha_4(\text{P161T})\beta_2\gamma_2 = 0.421 ± 0.061$ μM ($n = 14$); $\alpha_6N204I\beta_2\gamma_2 = 0.703 ± 0.078$ μM ($n = 11$), $P = 0.0001$) (Figure 2). As predicted, the $\alpha_1(\text{S206I})$ mutation decreased the amplitude of the maximum potentiation by midazolam by approximately 33% ($\alpha_1(\text{S206I})\beta_2\gamma_2 = 135.8 ± 23.8$%.

### Table 1 Midazolam Hill fit parameters for GABA$_A$ receptors with loop A-C mutations in the benzodiazepine site of $\alpha_1$-$6$. Data points were taken from midazolam concentration-response relationships (10-1000 nM) measured with whole-cell patch clamp recording of HEK293T cells expressing $\alpha_4\beta_2\gamma_2$ receptors

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<td>3.661 ± 1.897</td>
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<td>EC$_{50}$ (nM)</td>
<td>73.99 ± 3.44</td>
<td>h.n.f.</td>
<td>53.28 ± 5.54</td>
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<td>N</td>
<td>6</td>
<td>8</td>
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<td>$\alpha_5$</td>
<td>Max potentiation (%)</td>
<td>107.9 ± 20.3</td>
<td>h.n.f.</td>
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<td>Hill coefficient</td>
<td>2.632 ± 0.329</td>
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<td>EC$_{50}$ (nM)</td>
<td>52.84 ± 3.48</td>
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<td>53.28 ± 5.54</td>
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<td>$\alpha_6$</td>
<td>Max potentiation (%)</td>
<td>93.27 ± 22.84</td>
<td>h.n.f.</td>
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<td>2.310 ± 0.56</td>
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<td>EC$_{50}$ (nM)</td>
<td>41.88 ± 6.02</td>
<td>h.n.f.</td>
<td>41.88 ± 6.02</td>
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<tr>
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Fits were performed on each cell’s midazolam concentration response data. Midazolam concentration-response relationships not described by a sigmoidal function (h.n.f. = Hill Not Fit) were not included in our analysis (eg: no response or a linear nonsaturating response). Significance was determined using one-way ANOVA with Dunnett’s post hoc analysis for each $\alpha$-subunit and its mutations. **$P < 0.05$. Multiple comparisons were made relative to the wildtype $\alpha_4\beta_2\gamma_2$ receptor. The wildtype receptors containing $\alpha_4$ and $\alpha_6$ subunits lacked sigmoidal relationships and no statistics could be run to compare parameters from $\alpha_4(\text{R100H})$ and $\alpha_6(\text{R100H})$ datasets. Values are mean ± S.E.M. from N number of cells.
FIGURE 3 Mutations in loops A-C of the α subunit alter the degree of midazolam potentiation measured at α1β2γ2 GABA<sub>A</sub> receptors. (A) Example traces of midazolam (white boxes, 10-1000 nM) potentiating EC<sub>10</sub> GABA (black boxes) responses in wildtype α1β2γ2 receptors for α1-6. Whole-cell patch clamp recording was performed on HEK293T cells expressing α1β2γ2 receptors. Scale bars: 5 seconds, 500 pA. (B) Midazolam concentration-response curves from wildtype α1β2γ2 GABA<sub>A</sub> receptors for 10-1000 nM midazolam. Potentiation (%) was measured as the percent of enhancement in peak current evoked by EC<sub>10</sub> GABA. A 100% potentiation would be a doubling in current of the EC<sub>10</sub> GABA control response. Legend: α1 (●), α2 (○), α3(▲), α4(*), α5(□), α6(□). Points are mean ± SEM and where SEM is smaller than symbols, it is not visible. N = 9-17 cells per group. (C) Midazolam concentration-response curves from α1β2γ2 GABA<sub>A</sub> receptors containing loop A-C mutations and compared to their wildtype α1β2γ2 receptor counterparts. Potentiation (%) was measured as the percent of enhancement in peak current evoked by EC<sub>10</sub> GABA. Each line represents a different receptor condition: wildtype (black), loop A (red), loop B (green), and loop C (blue). Loop A mutations are α1(H102R), α2(H101R), α3(H126R), α4(R100H), α5(H105R), and α6(R100H). Loop B mutations are α1(T163P), α2(T162P), α3(T187P), α4(P161T), α5(P166T), and α6(P161T). Loop C mutations are α1(S206I), α2(S205I), α3(S230I), α4(I204S), α5(S209I), and α6(N204I). Points are mean ± SEM and where SEM is smaller than symbols, it is not visible. Sample sizes (cells per group) are: 9-14 (α1), 7-10 (α2), 6-17 (α3), 6-9 (α4), 7-11 (α5), and 6-8 (α6).
Midazolam is a benzodiazepine used to induce sedation and anesthesia. The therapeutically relevant range of midazolam measured from plasma is 75 ng/mL (207 nM, postoperative drowsiness) to 350 ng/mL (966 nM, anesthetized state). PAM benzodiazepines were initially thought to enhance the activity of GABA<sub>α</sub> receptors by altering the GABA binding steps, but more recent models have focused on gating mechanisms. The structural loops, loops A-C within the α subunit, define half of the benzodiazepine site on GABA<sub>α</sub> receptors. Understanding how different parts of the benzodiazepine site interact with modulators will help us better define the precise molecular mechanisms of these drugs.

In this study, we examined the role of the histidine in loop A, threonine in loop B, and serine in loop C within the α subunit and how these residues affected the allosteric potentiation of the GABA<sub>α</sub> receptor by midazolam. The histidine-to-arginine loop A mutation provided an example of how a single residue mutation can dramatically alter the efficacy of midazolam potentiation. The loop B threonine and loop C serine residues affected the allosteric potentiation of the GABA<sub>α</sub> receptors by midazolam. Overall, the mutation of the conserved threonine and serine in loop B, and serine in loop C within the α subunit and how these residues affected the allosteric potentiation of the GABA<sub>α</sub> receptor by midazolam. The histidine-to-arginine loop A mutation provided an example of how a single residue mutation can dramatically alter the efficacy of midazolam potentiation. The loop B threonine and loop C serine residues affected the allosteric potentiation of the GABA<sub>α</sub> receptors by midazolam.
Across the 18 mutations made in loops A-C within the benzodiazepine site, only subtle changes were seen in GABA apparent-affinity. Since the mutation was away from the GABA binding site, it is unlikely the mutations caused a structural rearrangement of the extracellular domain that affected the channel’s activation. The α6 (N204I) mutant increased the GABA’s apparent-affinity, but this was not sufficient to make the receptor any more responsive to midazolam than the wildtype α6-containing receptors. On the whole, our results were consistent with mutations that had minimal effects on GABA’s normal actions at the mutated receptor.

It is well-established that the conserved histidine present in loop A (FFHNG) of the α subunit is important in determining the molecular and behavioral effects of benzodiazepines. This histidine is present in the α subunits sensitive to positive benzodiazepines, but in α4 and α6 isoforms that are insensitive, an arginine is present that sterically inhibits benzodiazepines from interacting properly with the receptor. In our study, the histidine-to-arginine mutations in α1-3 and α5 abolished midazolam potentiation, consistent with prior studies using diazepam. Conversely, mutating the conserved arginine-to-histidine in α4 and α6 conferred midazolam potentiation capabilities to α4(R100H) and α6(R100H)-containing α1β2γ2 receptors. These results provided an example of how a single residue mutation could dramatically alter the efficacy of midazolam potentiation across receptors containing α1-6 isoforms.

One difficult aspect of measuring midazolam potentiation is choosing a drug application time that is sufficient to reach peak activation but avoids excessive desensitization and incomplete washout between applications. The 3 second midazolam exposure time used here, tried to balance these concerns while staying consistent across all receptor combinations used. Although incomplete peak responses at middle midazolam concentrations could result in a slightly underestimated EC50, the conclusions drawn here focus on the maximum potentiation measured at saturating midazolam concentrations as an estimation of drug efficacy.

In this study, the threonine (GSYAYTR, loop B) and serine (SSTGEYV, loop C) mutations had more subtle effects on midazolam potentiation than the α1H102R mutation. Our loop B results showed that only the α1(T163P) mutation decreased the maximum amplitude of midazolam potentiation as predicted. Of the other loop B mutations, α3(T187P) only slightly decreased the maximum potentiation, while α5(P166T) slightly increased it. Our results were consistent with the threonine in loop B conferring slightly higher midazolam efficacy to the receptor than the proline. This is consistent with a proline-to-threonine mutation in α5 and α6 that moderately increased zolpidem binding affinity in previous studies.

The loop C mutation had more obvious changes in the efficacy of midazolam potentiation. The wildtype α1, α2, α3, and α5 subunits all contain the homologous Ser206 (human α1) that we predicted would reduce midazolam potentiation when mutated to an isoluecine. Surprisingly, the results did not follow the predicted pattern. In the α1(S206I) and α2(S205I) mutants, the isoluecine decreased midazolam’s maximum potentiation by 31-33%, but in α3(S230I) and α5 (S209I), it increased midazolam’s potentiation by approximately 63%. Only α3(S230I) significantly (P < 0.05) altered midazolam’s EC50. In the case of an allosteric modulator, an altered EC50 might be caused by changes in the modulator’s ability to bind and interact with the receptor or the modulator’s ability to alter GABA’s binding and gating of the channel. As mentioned above, only modest changes in GABA apparent-affinity were seen for loop C mutations, suggesting that any changes in midazolam potentiation were more likely caused by an altered midazolam-receptor interaction and not global alterations in structure that transmitted to the GABA binding site.

Loop C is important for ligand binding because it has more mobility than the other loops and may affect benzodiazepine ligand selectivity. Previous studies found that the α6(Asn204) and α4(Ile203) residues (both homologous to human α1(Ser206)) were important for distinguishing the binding of negative benzodiazepines. Ser206 also physically interacts with diazepam in α1, α2 and α5, suggesting a critical role in benzodiazepine action. However, a neighboring mutation, homologous to α1(T207C), specifically altered benzodiazepine efficacy and not binding. We propose that the homologous Ser206 in loop C may provide an important point of contact between the ligand and benzodiazepine site that affects the coupling of the benzodiazepine site to GABA activation, thereby affecting the benzodiazepine’s efficacy. Because the effect of mutations in α3 and α5 were most dramatic, this serine may be more appropriately positioned in these subunits to alter midazolam’s efficacy.

The α3 and α5 subunits have specific expression profiles in the brain that reflect their roles in cognitive- and limbic-related pathways. The α3 subunit is expressed in the cortex, amygdala, olfactory bulb, and thalamic reticular nucleus, where α3β2γ2 receptors mediate phasic inhibition. The α5 subunit is most highly expressed in the pyramidal hippocampal cells but also in the cortex and hypothalamus. The α3β2γ2 receptors contribute to tonic inhibition in the hippocampus and have increasingly been studied for their role in cognition and anesthetic-induced neurotoxicity. In our results, the greatest increase in midazolam’s efficacy was seen with the α3(S230I) loop C mutation. The wildtype α3-containing receptors were the most sensitive to modulation by midazolam with the lowest midazolam EC50 and highest maximum potentiation relative to the other α subunits. This is consistent with previous studies where diazepam and flunitrazepam potentiated α2β2γ2 receptors more than α1β2γ2 receptors. Even with the higher wildtype levels of midazolam potentiation, the α3(S230I) loop C results were still notable. The α3(S230I) mutation in loop C dramatically increased the efficacy of midazolam potentiation compared to α2(S205I) (Figure 4) despite both α2β2γ2 and α3β2γ2 wildtype receptors having similar GABA apparent-affinities (Figure S2). This novel finding underscores the importance of better understanding the differences in allosteric modulation of GABA receptors expressing α3 compared to other α subunits. For example, nonhypnotic drugs targeting the α2 and α3 subunits have been studied for their anxiolytic and analgesic effects. However, creating ligands that distinguish these two subunits remains difficult, as shown when an
“α3-specific” PAM (SB-205384) was found to potentiate α6-containing GABA<sub>A</sub> receptors even more strongly than α3. Another way to distinguish different GABA<sub>A</sub> receptor subtypes is through the γ subunit. Although other γ subunits can form benzodiazepine-sensitive receptors, the γ3 subunit is less prevalent (~14% of receptors),<sup>37</sup> and the γ1 subunit notably reduces the benzodiazepine affinity of the receptor.<sup>48</sup> The γ2 subunit is the major γ isoform expressed in native GABA<sub>A</sub> receptors,<sup>49</sup> and thus α<sub>6</sub>β<sub>2</sub>γ<sub>2</sub> receptors provide a reasonable estimate of benzodiazepine efficacy in the brain. Based on our results, loop C might be a potential target for developing novel drugs that specifically modulate α<sub>3</sub>- and α<sub>5</sub>-containing GABA<sub>A</sub> receptors using PAMs targeting the allosteric benzodiazepine site.

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AUTHOR CONTRIBUTIONS

Participated in research design: O.A. Moody, A. Jenkins. Conducted experiments and data analysis: O.A. Moody. Wrote or contributed to the writing of the manuscript: O.A. Moody, A. Jenkins.

DISCLOSURES

None declared.

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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section at the end of the article.

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