

Alternative splicing generates two isoforms of the $\alpha 2$ subunit of the inhibitory glycine receptor

J. Kuhse^{1,2}, A. Kuryatov^{1,*}, Y. Maulet¹, M.L. Malosio^{1,**}, V. Schmieden^{1,2} and H. Betz¹

¹Zentrum für Molekulare Biologie Heidelberg, Universität Heidelberg, Im Neuenheimer Feld 282, D-6900 Heidelberg and

²Max-Planck Institut für Hirnforschung, Deutschordenstrasse 46, D-6000 Frankfurt 1, Germany

Received 5 March 1991

The inhibitory glycine receptor (GlyR) is a ligand-gated chloride channel protein which displays developmental heterogeneity in the mammalian central nervous system. Here we describe 2 novel cDNA variants of the rat GlyR $\alpha 2$ subunit and demonstrate that alternative splicing generates these 2 isoforms. The deduced protein sequences ($\alpha 2A$ and $\alpha 2B$) exhibit 99% identity with the previously characterized human $\alpha 2$ subunit. In situ hybridization revealed expression of both $\alpha 2A$ and $\alpha 2B$ mRNAs in the prenatal rat brain, suggesting that these variant proteins may have a role in synaptogenesis. Heterologous expression in *Xenopus* oocytes showed that the more abundantly expressed $\alpha 2A$ subunit forms strychnine-sensitive ion channels which resemble human $\alpha 2$ subunit GlyRs in their electrophysiological properties.

Glycine receptor; Alternative splicing; Receptor heterogeneity; Brain development

1. INTRODUCTION

The inhibitory glycine receptor (GlyR) is a ligand-gated chloride channel which antagonizes depolarization of the postsynaptic membrane in spinal cord and other regions of the vertebrate central nervous system [1]. Sedimentation and crosslinking experiments have revealed a pentameric structure of this membrane protein which is assembled from ligand binding α subunits of 48 kDa and homologous β polypeptides of 58 kDa [2–6]. The ensemble of these subunits forms an anion selective membrane channel which opens upon binding of the agonistic amino acids glycine, taurine or β -alanine [7].

Immunological and molecular cloning data have disclosed heterogeneity of GlyR α subunits during development [8–10]. In spinal cord of adult rats, $\alpha 1$ and $\alpha 3$ subunit genes are expressed [5,9] whereas $\alpha 2^*$ mRNA is predominantly found in newborn animals [10]. In addition to this heterogeneity resulting from different GlyR α subunit genes, a splice variant of the $\alpha 1$ subunit has been described which originates from alternative splice acceptor site selection, thus producing

a novel potential phosphorylation site within the predicted cytoplasmic loop region of this protein [11]. Here we report the characterization of 2 rat α subunit cDNAs which are highly homologous to the previously described human $\alpha 2$ [12] and rat $\alpha 2^*$ [10] sequences. These $\alpha 2$ variants are generated by alternative splicing of 2 homologous exons, and differ in the primary structure of their extracellular domains. In situ hybridization with radiolabelled probes specific for $\alpha 2A$ and $\alpha 2B$ showed that these 2 isoforms are expressed during early brain development.

2. MATERIALS AND METHODS

2.1. RNA isolation

RNA was isolated from rat spinal cord and cortex using the method of Cathala [13]. Poly(A)⁺ RNA was enriched by chromatography on oligo(dT) cellulose.

2.2. Construction and screening of cDNA libraries

Two cDNA libraries were constructed from mRNA isolated from brain and spinal cord of newborn (P0) rats. The brain library was obtained by cloning size-fractionated cDNA into the lambda phage vector lambda gt10 while cDNA synthesized from spinal cord poly(A)⁺ RNA was directionally cloned into lambda ZAP II according to the protocols supplied with cDNA cloning systems from Pharmacia and Stratagene. Size fractionation of cDNAs was achieved either by gel filtration on a Sepharose CL 4B column (brain cDNA), or by separating the cDNA in an agarose gel followed by electroelution (spinal cord cDNA). From the spinal cord cDNA, 3 independent sublibraries were constructed which contained insert sizes of 6–10 kb (I), 2–6 kb (II) and 0.5–2 kb (III), respectively.

2.3. Isolation and sequencing of GlyR cDNAs

A ³²P-labelled *Xho*I fragment (1794 bp) of the rat GlyR $\alpha 2^*$ cDNA [12] was used to screen about 2×10^5 plaque forming units each, of the

Correspondence address: H. Betz, Max-Planck Institut für Hirnforschung, Deutschordenstrasse 46, D-6000 Frankfurt 1, Germany. Fax: (49) (69) 6704 433.

*Present address: Shemyakin Institute of Bioorganic Chemistry, USSR Academy of Sciences, 117871 GSP Moscow, USSR.

**Present address: Department of Pharmacology, University of Milano, I-20129 Milano, Italy.

Moreover, this cDNA contained a 5'-nontranslated region of 551 bp and a 3'-nontranslated region of 1250 bp. At positions 3143-3148, a putative polyadenylation signal AATAAA was found, indicating that this cDNA ($\alpha 2A$) might be almost complete at its 3' end.

Another hybridization-positive clone ($\alpha 2B$) was isolated from a rat brain cDNA library [14] whose sequence proved to be identical to the above-mentioned clones with the exception of a continuous short sequence region, where identity dropped to about 79%. Out of 22 amino acid positions encoded by this diverging part of the DNA sequence of $\alpha 2B$, only 2 residues were different between both variants. In $\alpha 2B$, an isoleucine is found at position 58 and an alanine at position 59, instead of valine and threonine residues, respectively, in the rat $\alpha 2A$ and $\alpha 2^*$ [10] and human $\alpha 2$ [13] proteins. Interestingly, the same isoleucine and alanine residues are conserved at the corresponding positions of the rat $\alpha 1$ [6] and $\alpha 3$ [9] subunits.

To investigate whether the difference between the sequenced cDNAs originates from an alternative splicing event, we isolated the corresponding region from the mouse genome. An 2 kb *EcoRI-HindIII* fragment subcloned from a recombinant lambda phage was

found to contain 2 variants of the putative exon 3 (Y. Maulet and B. Matzenbach, unpublished data) of the $\alpha 2$ gene, which were identical to the sequences found in the rat cDNA clones $\alpha 2A$ and $\alpha 2B$ (Fig. 2). These variant exons are separated by a short intervening sequence of 91 bp, and both are surrounded by proper splice acceptor and donor sequences (Fig. 2).

Two 45 bp antisense oligonucleotide probes specific for exons 3A and 3B were used to perform in situ hybridization experiments. Rat brain sections of different developmental stages were incubated with the radiolabelled oligonucleotides, and hybridizing RNA sequences located by autoradiography. These experiments demonstrated the expression of the $\alpha 2A$ sequence in various higher brain regions during pre- and postnatal development (Fig. 3). Unexpectedly, $\alpha 2A$ mRNA was strongly expressed in cortex, thalamus and hippocampus at embryonic day 19 (E19) and at birth (P0). Expression of $\alpha 2B$ transcripts was also mainly seen at prenatal day E19. At this stage, the regional distribution of both sequences appeared to be quite similar, although hybridization signals were significantly lower for the $\alpha 2B$ mRNA. At later postnatal stages, $\alpha 2A$ expression was clearly decreasing and $\alpha 2B$ transcripts were barely detectable, although a low basal level of expression may still persist (Fig. 3). To investigate the pharmacological properties of the rat GlyR $\alpha 2$ polypeptide, in vitro synthesized $\alpha 2A$ RNA was injected into *Xenopus* oocytes. After 2-5 days, the cells were analyzed for glycine responses by electrophysiology in the voltage clamp mode. Membrane currents were seen at glycine concentrations $< 100 \mu M$, with half-maximal responses being obtained at about $250 \mu M$, a value similar to those required for gating human $\alpha 2$ and mutated rat $\alpha 2^*$ GlyR proteins (data not shown; see refs [10,12]). Strychnine blocks the opening of channels formed by the rat and human $\alpha 1$ and the human $\alpha 2$ subunits at concentrations of 20-100 nM [10,12,17]. A similar inhibition of chloride currents was observed here upon expression of $\alpha 2A$ mRNA in the oocyte system indicating that the $\alpha 2A$ polypeptide forms strychnine-sensitive GlyR channels (data not shown).

4. DISCUSSION

The identification of 2 variants of the GlyR $\alpha 2$ subunit resulting from alternative exon selection corroborates alternative splicing as an important mechanism to generate GlyR heterogeneity. The conservation of splicing pathways in mouse and rat demonstrated in this paper suggests a crucial role of minor sequence variations in GlyR function. Interestingly, the novel exon 3B of the $\alpha 2$ gene identified here codes for amino acid residues which are conserved in rat $\alpha 1$ [5] and $\alpha 3$ [9] subunits at identical positions, thus supporting further the evolutionary conservation

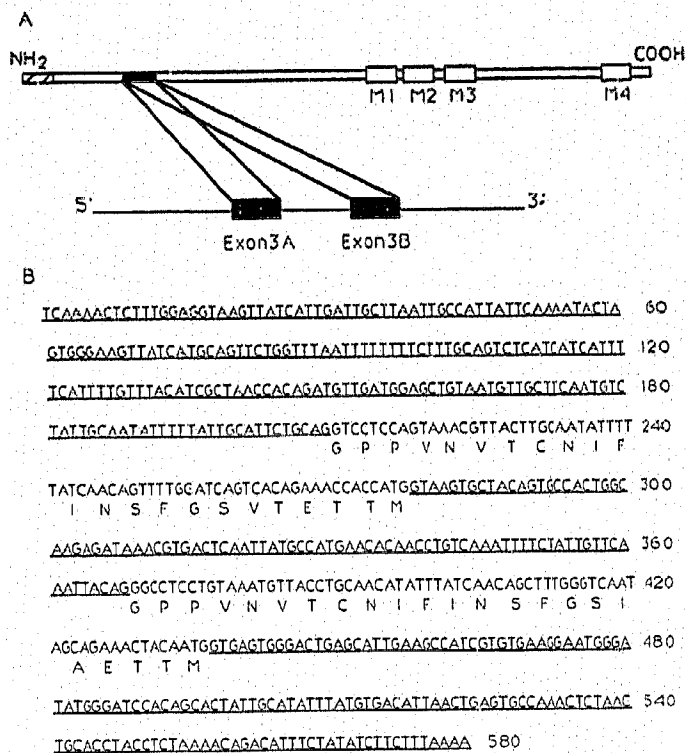
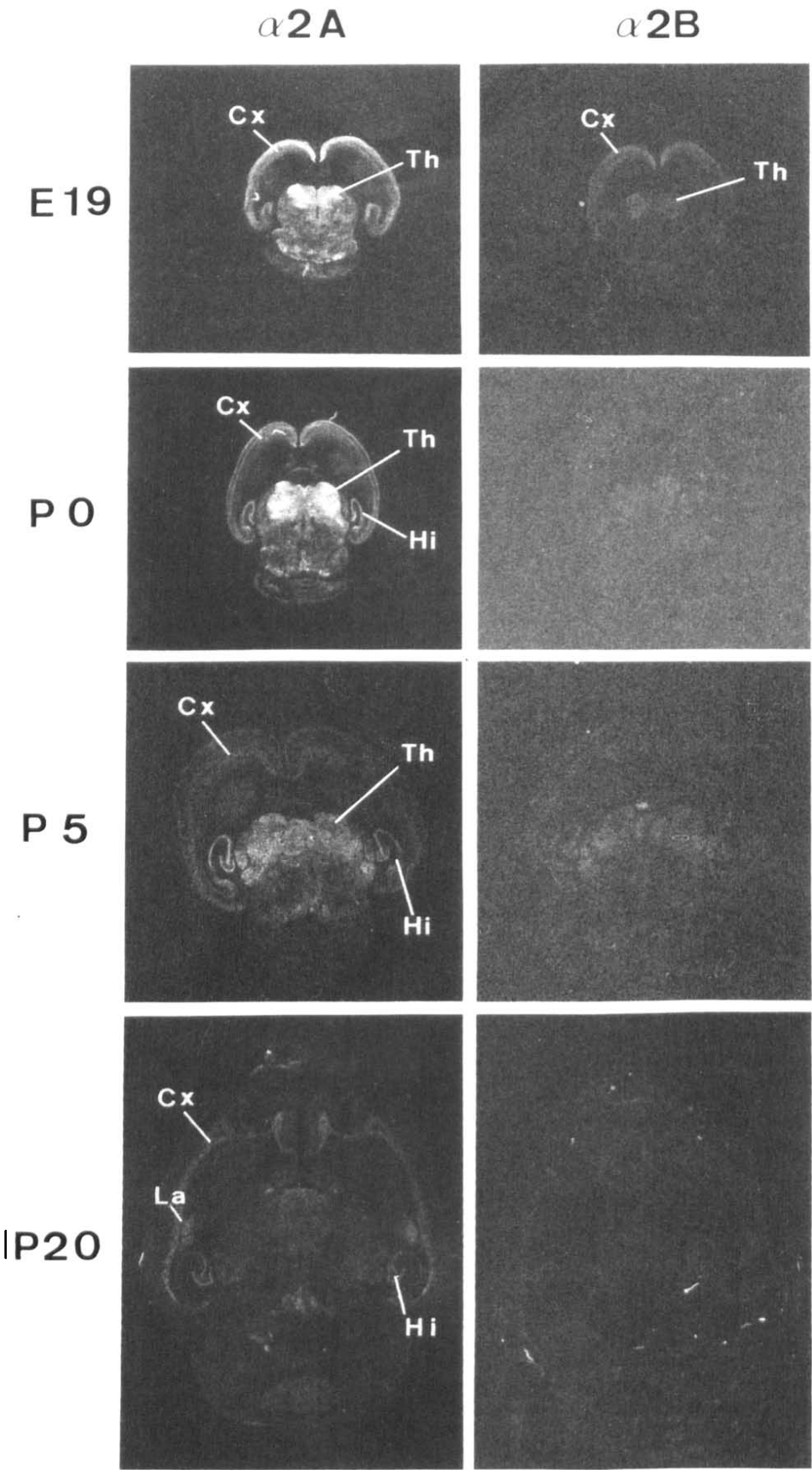


Fig. 2. (A) Schematic diagram of the position of exon 3 encoded amino acid residues in the primary structure of the GlyR polypeptide. Residues encoded by exons 3A or 3B are indicated by a black box; M1 to M4 shows positions of putative transmembrane regions of the GlyR. The signal peptide sequence is indicated by hatches. (B) Nucleotide sequence of the two exon 3 variants of the mouse $\alpha 2$ gene. Exonic regions are indicated by the encoded amino acid sequences, and intronic sequences are underlined.



of this subunit domain. Comparison of our data with alternative splicing events reported for other ligand gated ion channel proteins [18-21] raises the question whether similar exon variations might exist in GlyR $\alpha 1$ and $\alpha 3$ subunit genes. Indeed, alternative splicing cassettes have recently been shown to be conserved in the kainate/AMPA class of glutamate receptors and found to determine the functional properties of the resulting channels [22]. If so, alternative exon usage may constitute a general mechanism to provide plasticity of synaptic connections, a function which probably evolved before subunit diversification via gene duplication.

In a previous report, we have analyzed a GlyR subunit sequence termed $\alpha 2^*$ which is highly expressed in the spinal cord of newborn, but not adult, rats [10]. As shown above, $\alpha 2^*$ and $\alpha 2A$ cDNA sequences are identical except for an A to G substitution at position 1132, which results in a glycine residue at position 167 in the $\alpha 2A$ protein instead of a glutamate in the $\alpha 2^*$ polypeptide. Besides, a further nucleotide exchange was found in the 5' nontranslated region (pos. 371 G/C). Thus, the PCR amplification experiments in our earlier studies [10] did not distinguish between $\alpha 2A$, $\alpha 2B$ and $\alpha 2^*$ subunits, and all these $\alpha 2$ sequences might indeed be expressed at early stages of spinal cord development. This assumption is supported by in situ hybridization experiments with $\alpha 2A$ and $\alpha 2B$ specific oligonucleotides on spinal cord sections which produced clear hybridisation signals for both probes at early postnatal stages (M.L. Malosio, unpublished data). As demonstrated previously by site-directed mutagenesis, the glutamate residue at position 167 of the $\alpha 2^*$ subunit causes a loss of a strychnine sensitivity of the receptor upon expression in *Xenopus* oocytes [10]. We therefore had proposed that the $\alpha 2^*$ sequence might correspond to the ligand-binding subunit of the biochemically characterized neonatal GlyR, which displays only low affinity binding of the antagonist strychnine [8]. As the sequences of the $\alpha 2A$ and $\alpha 2^*$ cDNAs are identical besides 2 nucleotide substitutions in the 5' nontranslated and the coding regions, it seems unlikely that 2 genes of nearly identical sequence exist in the rat genome. We therefore speculate that $\alpha 2^*$ and $\alpha 2$ mRNAs may represent allelic variations of the same $\alpha 2$ subunit gene. This would be one possible explanation for the isolation of $\alpha 2^*$ and $\alpha 2A$ cDNAs, which now is under investigation in our laboratory.

The in situ hybridization experiments with brain sections from pre- and postnatal rats performed here

revealed strong signals in higher brain regions. Cortical layers in forebrain were labelled by both the $\alpha 2A$ and $\alpha 2B$ probes already at E19. During further development, $\alpha 2B$ transcripts appeared to be down-regulated, whereas $\alpha 2A$ gene expression remained well detectable beyond early postnatal stages and was still seen in the hippocampus and thalamus of P20 rats. Thus, the $\alpha 2A$ and $\alpha 2B$ subunit variants may have different roles during synapse formation in the mammalian brain.

Acknowledgements: We thank P. Seeburg for providing the rat brain cDNA library, M. Munz for technical assistance, I. Baro and J. Rami for secretarial assistance, and D. Langosch for critical reading of the manuscript. This work was supported by Deutsche Forschungsgemeinschaft (SFB 317 and Leibniz-Programm), Bundesministerium für Forschung und Technologie (BCT 363/1) and Fonds der Chemischen Industrie.

REFERENCES

- [1] Betz, H. and Becker, C.-M. (1988) *Neurochem. Int.* 13, 137-146.
- [2] Pfeiffer, F., Graham, D. and Betz, H. (1982) *J. Biol. Chem.* 257, 818-823.
- [3] Graham, D., Pfeiffer, F., Simler, R. and Betz, H. (1985) *Biochemistry* 24, 990-994.
- [4] Langosch, D., Thomas, L. and Betz, H. (1988) *Proc. Natl. Acad. Sci. USA* 85, 7394-7398.
- [5] Grenningloh, G., Rienitz, A., Schmitt, B., Methfessel, C., Zensen, M., Beyreuther, K., Gundelfinger, E.D. and Betz, H. (1987) *Nature* 328, 215-220.
- [6] Grenningloh, G., Pribilla, I., Prior, P., Multhaup, G., Beyreuther, K., Taleb, O. and Betz, H. (1990) *Neuron* 4, 963-970.
- [7] Aprison, M.H. and Daly, E.C. (1978) *Adv. Neurochem.* 3, 203-294.
- [8] Becker, C.-M., Hoch, W. and Betz, H. (1988) *EMBO J.* 7, 3717.
- [9] Kuhse, J., Schmieden, V. and Betz, H. (1990) *J. Biol. Chem.* 265, 22317-22320.
- [10] Kuhse, J., Schmieden, V. and Betz, H. (1990) *Neuron* 5, 867-873.
- [11] Malosio, M.-L., Grenningloh, G., Kuhse, J., Schmieden, V., Schmitt, B., Prior, P. and Betz, H. (1991) *J. Biol. Chem.* 266, 2048-2053.
- [12] Grenningloh, G., Schmieden, V., Schofield, P.R., Seeburg, P.H., Siddique, T., Mohandas, T.K., Becker, C.-M. and Betz, H. (1990) *EMBO J.* 9, 771-776.
- [13] Cathala, G., Savouret, J.-F., Mendez, B., West, B.L., Karin, M., Martial, J.A. and Baxter, J.D. (1983) *DNA* 2, 329-335.
- [14] Ymer, S., Schofield, P.R., Draguhn, A., Werner, P., Köhler, M. and Seeburg, P.H. (1989) *EMBO J.* 8, 1665-1670.
- [15] Sanger, F., Nicklen, S. and Coulson, A.R. (1977) *Proc. Natl. Acad. Sci. USA* 74, 5463-5467.
- [16] Wisden, W., Morris, B.J. and Hunt, S.P. (1991) in: *Molecular Neurobiology - A Practical Approach* (Chad, J. and Whead, H. eds) vol. 2, IRL Press, Oxford, pp. 205-225.
- [17] Schmieden, V., Grenningloh, G., Schofield, P.R. and Betz, H. (1989) *EMBO J.* 8, 695-700.
- [18] Goldmann, D., Deneris, E., Luyten, W., Kochhar, A., Patrick, J. and Heinemann, S. (1987) *Cell* 48, 965-973.
- [19] Goldmann, D. and Tamai, K. (1989) *Nucleic Acids Res.* 17, 3049-3056.
- [20] Beeson, D., Morris, A., Vincent, A. and Newson-Davis, J. (1990) *EMBO J.* 9, 2101-2106.
- [21] Whiting, P., McKernan, R.M. and Iversen, L.L. (1990) *Proc. Natl. Acad. Sci. USA* 87, 9966-9970.
- [22] Sommer, B., Keinänen, K., Verdoorn, T.A., Wisden, W., Burnashev, N., Herb, A., Köhler, M., Takagi, T., Sakmann, B. and Seeburg, P.H. (1990) *Science* 249, 1580-1585.

Fig. 3. In situ hybridization of GlyR subunit mRNAs in horizontal sections of rat brain using antisense oligonucleotide probes specific for $\alpha 2A$ and $\alpha 2B$ GlyRs. Hybridizations to sections from a late prenatal (E19) and 3 postnatal (P0, P5 and P20) stages are shown. Cx, cortex; Hi, hippocampus; La, lateral amygdaloid nucleus; Th, thalamus. Exposure on X-Omat AR film was for 8 weeks.