

## **Constraining the expression of nicotinic acetylcholine receptors using pentameric constructs**

Paul J. Groot-Kormelink, Steven Broadbent, Marco Beato, and Lucia G. Sivilotti

*Dept. of Pharmacology, University College London, Gower Street, London, WC1E 6BT,*

*U.K. (P.J.G-K, S.B, M.B and L.G.S.)*

*Running title* Expression of nicotinic receptors from pentameric constructs

Correspondence should be addressed to Lucia Sivilotti, Dept. of Pharmacology,  
University College London, Gower Street, London, WC1E 6BT, U.K., tel. 0044 20 7679  
3693, fax 0044 20 7679 7298, e-mail [l.sivilotti@ucl.ac.uk](mailto:l.sivilotti@ucl.ac.uk)

Number of text pages: 26

Number of tables: none

Number of figures: 4

Number of references: 25

Number of words in the *Abstract*: 151

Number of words in the *Introduction*: 390

Number of words in the *Discussion*: 1013

### ***Abstract***

Much of our understanding of ligand-gated ion channels comes from heterologous expression studies. However, this technique cannot produce receptors with a predetermined subunit composition for channels formed by several different subunits and cannot insert a single mutation copy if the subunit of interest is present in several copies in the channel. Here we describe a novel approach that overcomes these problems by expressing pentameric constructs, in which the code of the five subunits is linked (i.e.  $\beta 4_{\beta 4_{\alpha 3}_{\beta 4_{\alpha 3}}}$ ). This is the first time that a concatemer of the complete pentameric receptor has been expressed for channels in the Cys-loop superfamily. The presence of the linker did not change the agonist or antagonist sensitivity of  $\alpha 3\beta 4$  nicotinic receptors. We show evidence that the expressed receptors were made up of  $\alpha 3$  and  $\beta 4$  subunits in one pentameric fusion protein as designed in the construct. This approach can be applied to any nicotinic superfamily receptor to produce channels with a defined subunit arrangement and to introduce specific mutations at any desired location of the pentameric fusion protein.

## ***Introduction***

It is hard to exaggerate the importance of heterologous expression in the study of ion channels. *Xenopus* oocytes or mammalian cells transfected with the appropriate constructs express the receptor of interest almost in isolation and in conditions ideal for electrophysiological recording. Much of our understanding of channel subunit composition and of structure-function relation comes from such work.

If the subunit combination is right, the functional properties of many synaptic channels are reproduced surprisingly faithfully by expression in non-neuronal cells. Only now are the limitations of this technique in its simplest form beginning to emerge and to constrain our experiments. One frustrating problem is that of reproducing channels with complex or variable subunit composition, such as neuronal nicotinic receptors (nAChR).

Functional heteromeric neuronal nAChRs can be formed by expression of an  $\alpha$  and a  $\beta$  subunit (Colquhoun *et al.*, 2003), but native receptors can contain as many as four different subunits (Conroy and Berg, 1995; Forsayeth and Kobrin, 1997; Moretti *et al.*, 2004). Furthermore, the  $\alpha$  to  $\beta$  ratio in the pentamer may depend on the expression system and the transfection ratio (Zwart and Vijverberg, 1998; Nelson *et al.*, 2003).

Another problem is that channels often contain more than one copy of the same subunit. For instance, the muscle nAChR has two copies of the main binding subunit,  $\alpha$ . This means that we cannot easily produce muscle receptors bearing just one mutant  $\alpha$  subunit and therefore we cannot easily study the role of each binding site.

There have been several attempts to solve these problems by expressing concatameric constructs, namely by linking subunit cDNAs in order to obtain fusion proteins, which in principle can be incorporated in the receptor only in a restricted range of combinations

(Im *et al.*, 1995; Baumann *et al.*, 2001; Baumann *et al.*, 2002; Baumann *et al.*, 2003; Nelson *et al.*, 2003; Minier and Sigel, 2004). A number of problems have come to light with this approach, such as proteolysis (Nicke *et al.*, 2003), dipentamer formation (Zhou *et al.*, 2003) and incomplete incorporation of fusion proteins, a problem which can be hard to detect (Groot-Kormelink *et al.*, 2004). In the nicotinic superfamily, concatemeric approaches have so far focussed on lower order concatemers (subunit dimers and trimers). Here we report the success of an alternative approach that for the first time links all the subunits into a pentameric construct.

## ***Materials and Methods***

### *Construction of Pentameric Subunit cDNAs*

The human  $\alpha 3$  and  $\beta 4$  nicotinic subunits (Genbank Y08418 and Y08416), containing only coding sequences and an added Kozak consensus sequence (GCCACC) immediately upstream of the start codon, were subcloned into the pcDNA3.1 (Invitrogen) and the pSP64GL vectors. Mutants were created using the QuickChange™ Site-Directed Mutagenesis Kit (Stratagene) and full-length sequenced.

Pentameric constructs were produced from intermediate tandem and trimer constructs.

All tandem constructs ( $\alpha 3_{\beta 4}$ ,  $\beta 4_{\alpha 3}$ , and  $\alpha 3_{\alpha 3}$ ) were made in the same way. First, the coding region of each subunit was amplified by PCR excluding the stop codon. The PCR primers directed to each corresponding start codon included the Kozak sequence (GCCACC) and the EcoRI restriction site (5' end PCR-fragment; CTGAATTCGCCACCATG.....). The primer directed to the coding sequence upstream of the stop codon included the NotI restriction site (basically replacing the stop codon by the NotI site). The resulting DNA-fragments were purified and subcloned into the pcDNA3.1/Myc-His version C vector (Invitrogen), using the EcoRI and NotI restriction sites. A linker DNA-fragment (Im et al., 1995) was created by hybridization of two complementary oligonucleotides; 5'-

GGCCGCTCAGCAACAGCAGCAACAGCAGCAAG-3' and 5'-

AATTCTTGCTGCTGTTGCTGCTGTTGCTGAGC-3'. The resulting double strand

DNA linker contains a 5'-end NotI restriction site overhang (underlined) and a 3'-end

EcoRI restriction site overhang (underlined), separated by 25 nucleotides (the first

nucleotide (bold) is inserted to bring the NotI site (8-cutter) back in the correct reading

frame, whereas the next 24 nucleotides code for 8 glutamines). The tandem constructs were created using three unique restriction sites; EcoRI (upstream of the start codon of all subunits and the 3'-end of the linker), NotI (downstream of the coding sequence of all subunits and the 5'-end of the linker) and AgeI (between the Myc and His epitope sequences in the pcDNA3.1/Myc-His version C vector). A three way ligation resulted in the following tandem circular plasmid; \* [**AgeI** .. His-epitope .. stop codon .. pcDNA3.1/Myc-His C vector .. EcoRI - *subunit A* - **NotI**] \* [**NotI** – linker - **EcoRI**] \* [**EcoRI** - *subunit B* – NotI .. Myc-epitope .. **AgeI**] \* (where \* represents the ligation sites and [ ] represents purified DNA fragments digested with the restriction sites indicated in bold). In order to remove the epitope tags (Myc- and His-) all tandems were subcloned in the corresponding pcDNA3.1 vector, using a unique restriction site in subunit B. For instance cutting the tandem upstream of the start codon (of subunit A) and somewhere in subunit B and transferring this fragment in the same position of subunit B, previously cloned in the pcDNA3.1 vector. Finally all tandem constructs were also subcloned in the pSP64GL vector. 9' mutant tandems were created by swapping the corresponding DNA fragments (using unique restriction sites upstream and downstream of the L9'T mutation) from  $\alpha 3^{L279T}$  (for  $\beta 4\_ \alpha 3^{L279T}$ ) and  $\beta 4^{L272T}$  (for  $\beta 4^{L272T}\_ \alpha 3$ ). The  $\alpha 3\_ \beta 4$ ,  $\beta 4\_ \alpha 3$ ,  $\beta 4\_ \alpha 3^{L279T}$ , and  $\beta 4^{L272T}\_ \alpha 3$  tandem constructs cloned in the pSP64GL vector were fully sequenced.

Both trimer constructs were created by cutting and ligating different parts of the tandem and monomeric plasmids described above. The first trimer [ $\beta 4\_ \beta 4\_ \alpha 3$ / pSP64GL] was created by ligating three DNA-fragments;  $\beta 4\_ \alpha 3$ /pSP64GL\*EcoRI-XbaI (4583bp),  $\beta 4$ /pcDNA3.1/Myc-His\*EcoRI-ApaI (1486bp), and  $\beta 4\_ \alpha 3$ /pSP64GL\*XbaI/ApaI

(1814bp). The mutated [ $\beta 4^{L272T}$ \_ $\beta 4$ \_ $\alpha 3$ /pSP64GL] trimer was created as above except for the first DNA-fragment being  $\beta 4^{L272T}$ \_ $\alpha 3$ /pSP64GL\*EcoRI-XbaI (4583bp).

Pentameric constructs were created by cutting and ligating different parts of the tandem and trimer plasmid constructs described above. The first pentameric construct

[ $\beta 4$ \_ $\beta 4$ \_ $\alpha 3$ \_ $\beta 4$ \_ $\alpha 3$ /pSP64GL] was created by ligating three different DNA-fragments;

$\beta 4$ \_ $\beta 4$ \_ $\alpha 3$ /pSP64GL\*KspI-XbaI (6176bp),  $\alpha 3$ \_ $\beta 4$ /pcDNA3.1/Myc-His\*KspI-ApaI

(2986bp), and  $\beta 4$ \_ $\alpha 3$ /pSP64GL\*ApaI-XbaI (1814bp). Mutant pentameric constructs

[ $\beta 4^{L272T}$ \_ $\beta 4$ \_ $\alpha 3$ \_ $\beta 4$ \_ $\alpha 3$ /pSP64GL,  $\beta 4$ \_ $\beta 4$ \_ $\alpha 3$ \_ $\beta 4$ \_ $\alpha 3^{L279T}$ /pSP64GL, and

$\beta 4^{L272T}$ \_ $\beta 4$ \_ $\alpha 3$ \_ $\beta 4$ \_ $\alpha 3^{L279T}$ /pSP64GL] were created as above except for using the

corresponding mutated  $\beta 4$ \_ $\alpha 3^{L279T}$ /pSP64GL and/or  $\beta 4^{L272T}$ \_ $\beta 4$ \_ $\alpha 3$ /pSP64GL DNA-

fragments. All trimer and pentameric constructs were checked for cloning artifacts by a minimum of five different restriction enzyme digests.

*RNA Gel-Electrophoresis*—Capped cRNA was prepared as previously described

(Boorman *et al.*, 2000). For RNA electrophoresis (1.5% agarose gel, 1X Gel

Prep/Running buffer, NorthernMax-Gly™, Ambion), RNA samples (including the 0.24-

9.5 Kb RNA ladder, Gibco.BRL) were diluted 1:1 with Glyoxal sample loading dye

(Ambion) and incubated at 50°C for 30 minutes before loading. Samples were separated

at 5 V/cm for 3 hours and RNAs were visualized by UV-transillumination.

### *Electrophysiological Recording and Analysis*

*Xenopus* oocyte harvesting, preparation and two-electrode voltage clamp recording were

as previously described (Boorman *et al.*, 2000). The quantity of cRNA injected was from



0.05 to 0.9 ng for  $\alpha 3$ ,  $\alpha 3^{L279T}$ ,  $\beta 4$ ,  $\beta 4^{L272T}$ , and  $\beta 4\_ \alpha 3^{L279T}$  constructs and up to 100 ng cRNA for the pentameric constructs. Recording was done at a -70 mV, in nominally 0-calcium Ringer solution (mM: NaCl 150, KCl 2.8, HEPES 10, MgCl<sub>2</sub> 2, atropine sulphate 0.5  $\mu$ M, Sigma; pH 7.2). Trimetaphan was bath-applied for 25 minutes before responses to ACh were obtained (in the continued presence of antagonist). ACh concentration-response curves were obtained in a descending dose protocol and the resulting data fitted with a Hill equation with the program CVFIT (Colquhoun and Vais, <http://www.ucl.ac.uk/pharmacology/dc.html>). Values reported are means ( $\pm$  standard deviation of the mean) of the results of fitting each dose-response curve separately (Boorman *et al.*, 2000).

## Results

*Receptors expressed from pentameric constructs are similar to those expressed from monomer constructs*

*Fig.1-here*

Figure 1a-b shows ACh current responses from oocytes expressing human  $\alpha 3\beta 4$  neuronal nAChRs from monomer  $\alpha 3 + \beta 4$  constructs (top) or from the pentamer construct  $\beta 4\_ \beta 4\_ \alpha 3\_ \beta 4\_ \alpha 3$ . Agonist responses were very similar for the two receptors both in time course and agonist sensitivity. Analysis of the concentration-response curves (Fig. 1c) showed a small difference in  $EC_{50}$  ( $137.8 \pm 13.7 \mu M$  vs.  $95.0 \pm 10.7 \mu M$ ,  $n=4$  and  $6$ , for the monomer and pentamer constructs, respectively;  $P=0.038$ , two-tailed Student  $t$ -test), but not in Hill slope ( $1.79 \pm 0.14$  and  $1.71 \pm 0.13$ ).

Measuring agonist  $EC_{50}$  values is a fairly unsatisfactory way of comparing receptors. A much more robust technique for determining the integrity of the binding site is to measure the shift produced by a competitive antagonist (such as trimetaphan) in the concentration dependence of agonist responses (i.e. dose-ratios). Dose-ratios to  $0.2 \mu M$  trimetaphan are very similar in monomer- and pentamer-expressed receptors, with values of  $4.35 \pm 0.38$  and  $5.01 \pm 0.37$ , respectively (monomer construct values from Boorman *et al.*, 2003). Because the magnitude of this shift is a direct expression of antagonist affinity, this indicates that the (overlapping) agonist/antagonist binding site is very similar in the two types of recombinant receptors.

*Functional receptors expressed from pentameric constructs are not formed by breakdown products or by incomplete incorporation of the fusion protein*

We recently showed (Groot-Kormelink *et al.*, 2004) that tandem subunit incorporation in nAChRs can be incomplete and that this problem is hard to detect. Hence we extensively tested whether this problem occurs for pentameric construct receptors and whether these receptors contain the correct complement of subunits as dictated by the construct design. First we checked if the *in vitro* synthesised cRNA was of the correct length and that no RNA breakdown had happened. Conceivably, if there is sufficient contamination by breakdown products, the functional receptors we observed may not be produced by the linked, five-subunit construct as we wish, but by the contaminant.

*Fig.2-here*

cRNA gel electrophoresis (Figure 2) indicated that construct impurity or breakdown was not a problem, as all constructs used showed one clean band of the appropriate molecular weight.

Of course, degradation may occur *after* injection into the oocyte or at protein level and could still make pointless our effort to constrain receptor topology and composition. A straightforward way of testing this would be to check the size of either the individual proteins (by Western blotting) or the assembled complex (by sucrose-gradient separation). The other possibility was to devise a functional test for the presence of breakdown products and for incomplete pentamer incorporation. We chose to do that in

the hope that a functional test would be more sensitive in detecting what may be relatively low levels of breakdown products. Furthermore, such a test would detect only those channels that are on the surface of the oocyte and are functional. The approach we chose relies on a reporter mutation: incorporation of the mutation we selected (L9'T in the second transmembrane domain) into  $\alpha 3\beta 4$  nAChRs increases agonist sensitivity (Boorman *et al.*, 2000).

*Fig.3-here*

Thus we added an excess of a single mutant monomer cRNA, either  $\alpha 3^{LT}$  or  $\beta 4^{LT}$ , to the pentamer construct. The addition of mutant monomers would reveal the presence of a significant level of (functional) degradation products (such as lower order concatamers or single subunits) by incorporating them into receptors. Such receptors would carry mutations and would be distinguishable from the wild-type receptors produced by the pentamer construct alone. Figure 3 shows that no such mutant receptors could be detected when either  $\alpha 3^{LT}$  or  $\beta 4^{LT}$  subunits were expressed together with the pentamer. Thus  $EC_{50}$  values were not changed by expression with mutant subunits and were  $99.6 \pm 10.7$  and  $84.6 \pm 7.6 \mu M$  for pentamer constructs co-injected with  $\alpha 3^{LT}$  or  $\beta 4^{LT}$ , respectively ( $n = 4$  for both).

In order to maximise the sensitivity of this test, we chose to inject an excess of monomer mutant subunit constructs. Because efficiency of expression and incorporation are much greater for the monomer construct, considering simply the ratio between the quantity of cRNA injected for monomer and pentamer grossly underestimates the “functional”

excess in monomer. A better quantification is given by the level of functional expression achieved by the different constructs. Thus we determined empirically the amount of cRNA to be injected in order to have (Figure 3, top) a functional expression of monomers (estimated by measuring maximum ACh responses, i.e. to 1 mM ACh) approximately an order of magnitude larger than that of monomer plus pentamer. Thus, 0.25 ng of  $\alpha 3^{LT}$  or  $\beta 4^{LT}$  cRNA produced several  $\mu A$  of current if injected together with 0.25 ng of the appropriate wild type monomer ( $5570 \pm 890$  nA,  $n = 10$  and  $2342 \pm 393$  nA,  $n = 6$ , respectively) but only approximately half a  $\mu A$  if injected with 100 ng pentamer cRNA ( $570 \pm 151$  and  $621 \pm 97$  nA, respectively). As detailed above, this approximately ten-fold excess of mutant monomer failed to affect the receptor dose-response curve. Another concern was that degradation of the construct or of the fusion protein could lead to the formation of a fragment, such as  $\beta 4\text{-}\beta 4\text{-}\alpha 3$ , that would require both an  $\alpha$  and a  $\beta$  subunit for functional assembly and detection. This was tested by injecting the pentamer construct together with an excess of  $\beta 4\text{-}\alpha 3^{LT}$  construct. No shift in the resulting dose-response curves was observed, indicating that  $\beta 4\text{-}\alpha 3^{LT}$  does not incorporate and therefore a  $\beta 4\text{-}\beta 4\text{-}\alpha 3$  fragment is not present (data not shown). More indirect evidence that functional expression is not due to the assembly of lower-order breakdown products comes from the fact that another pentameric construct that we tested ( $\alpha 3\text{-}\beta 4\text{-}\alpha 3\text{-}\beta 4\text{-}\alpha 3$ ) failed to produce functional receptors.

These experiments not only suggest that breakdown does not occur or is very limited, but also confirm that pentameric construct receptors contain the pentameric fusion protein in its entirety, as intended. If this was not the case and more than one pentamer participated

to the formation of a single receptor, for instance contributing one or two subunits, we would expect to see preferential incorporation of (mutant) monomer constructs into such receptors and therefore shifts in the dose-response curves. This is because monomer subunits incorporate with high efficiency when competing with tandem constructs, even when they are not in excess (Groot-Kormelink *et al.*, 2004).

*Exploiting the potential of pentamer constructs: subunit non-equivalence*

Many ligand-gated channels of the nicotinic superfamily contain multiple copies of one subunit, and with conventional expression techniques it is impossible to mutate only one of these subunit at a time and choose the location of the mutant subunit. This difficulty is overcome by using pentamer constructs, which allow us to determine the number and position of the mutations inserted.

We met with this limitation in our previous characterisation of L9'T mutations in neuronal nAChRs. In unlinked  $\alpha\beta\beta\beta\beta$  receptors (Boorman *et al.*, 2000), interpolation of the effect of mutating all  $\alpha$  or all  $\beta$  subunits (with the assumption of equivalence within subunit subtype) gave similar unitary shifts for  $\alpha$  and  $\beta$ , of 5.6 and 6.2-fold, respectively. We have now tested the effect of introducing a single L9'T mutation in the  $\alpha\beta\beta\beta\beta$  receptor.

Concentration-response curves (Figure 4) show that the effect of a single mutation is much greater if it the mutation is carried by the  $\alpha$  subunit ( $\beta\beta\alpha\beta\alpha^{LT}$  construct) than if it is carried by the  $\beta$  subunit ( $\beta^{LT}\beta\alpha\beta\alpha$  construct). Receptors with a mutation in

$\alpha$  have an ACh sensitivity 16-fold greater than wild type ( $EC_{50}$   $5.9 \pm 0.2 \mu\text{M}$ ,  $n = 4$ ), whereas, for receptors with one  $\beta$  mutation, sensitivity increases only roughly three-fold ( $EC_{50}$  of  $28.5 \pm 1.8 \mu\text{M}$ ,  $n = 5$ ). Note that for both  $\alpha$  and  $\beta$ , the effect of a single mutation is different than the 6-fold shift predicted by the results of mutating all  $\alpha$ s or all  $\beta$ s (shown by the dotted lines in the graphs in Fig 4). These data strongly suggest that both the two  $\alpha$  and the three  $\beta$  subunits are non-equivalent in their pore-lining domain. Previously, asymmetry in the contribution of each subunit's TM2 residues to gating has been studied only in muscle nicotinic receptors (Labarca *et al.*, 1995; Grosman and Auerbach, 2000).

*Fig.4-here*

Fig. 4 (bottom graph) shows that the shifts in the position of the dose-response curve produced by mutating one  $\alpha$  and one  $\beta$  subunit multiply (i.e. add logarithmically). Thus the  $EC_{50}$  of  $\beta^{\text{LT}}\text{-}\beta\text{-}\alpha\text{-}\beta\text{-}\alpha^{\text{LT}}$  receptors was  $2.0 \pm 0.6 \mu\text{M}$ ,  $n = 4$ , corresponding to a 46-fold increase in agonist sensitivity.

All dose-response curves obtained for mutant pentameric constructs were well-fitted by one component fits. This suggests that they are likely to be produced by a single population of mutant receptors, containing the number of copies of the mutation intended when the construct was designed. This further confirms that these constructs express a single fusion protein that contains five subunits (i.e. there is no significant breakdown) and that these subunits are all assembled into one receptor that is functionally expressed

(i.e. the incomplete incorporation seen with our tandem approach does not occur, see Groot-Kormelink *et al.*, 2004).

### ***Discussion***

We report the successful functional expression of neuronal nAChRs from a pentameric construct, in which all the five subunits that form the receptor have been artificially linked. While expression of such a complete-receptor concatemer has been obtained for other channel types, notably potassium channels (Liman *et al.*, 1992), TRP channels (Hoenderop *et al.*, 2003) and P2X channels (Stoop *et al.*, 1999), to our knowledge this is the first time that this approach has been used for channels in the nicotinic superfamily.

Other work with linked constructs has focussed on lower-order concatemers, such as tandems (expressed with monomers) or trimers (expressed with tandems, see Minier and Sigel, 2004). We recently found that expressing  $\beta 4_{\alpha 3}$  tandem together with  $\beta 4$  does produce functional  $\alpha 3\beta 4$ -type nAChRs, but that these are not a homogeneous population, as a proportion suffer from incomplete incorporation of the tandem protein (Groot-Kormelink *et al.*, 2004). The fact that these pentamers did not contain one copy of monomer and two of tandem, as planned, was revealed only by an extensive series of reporter mutation tests. Incomplete incorporation was probably due to differences in the efficiency with which monomers and concatemers incorporate in the receptor. Therefore, while it is somewhat surprising that the more ambitious approach of a single full-length construct did produce functional channels, this approach should be less vulnerable to the problem of competition between monomers and different-order concatamers.



Our first concern was to make sure that the receptors were formed as designed in the construct, i.e. that each pentamer contained all the five subunits linked in the fusion protein and only those subunits. Other “unwanted” receptor assemblies could form through the incorporation of subunits produced by breakdown of the linked cRNA or protein (a problem reported for P2X concatamers, see Nicke *et al.*, 2003), through inefficient incorporation of the linked proteins (Groot-Kormelink *et al.*, 2004) and through the sharing of linked proteins across different receptors (Zhou *et al.*, 2003).

Because we wanted to focus on functional receptors, we tested for the formation of such unwanted pentamers by expressing with the pentamer construct a large excess of mutant monomer, either  $\alpha^{LT}$  or  $\beta^{LT}$  or tandem  $\beta4\_ \alpha3^{LT}$ . Our failure to detect incorporation of the mutation in pentamer-expressed receptors shows that the monomer subunit cannot insert itself into the final functionally-expressed pentamer. This also implies that incorporation of the “tail end” of the pentamer construct is preferred to the incorporation of the monomer subunit in completing the receptor. Also, breakdown does not produce enough single subunits to give a detectable level of functional channels, even when this is facilitated by an excess of added monomer cRNA. Because of our choice of experimental design, we cannot exclude that such “unwanted” pentamers do form, but are not functional. Nevertheless, this is not important for our purpose, which is to do functional receptor work.

The properties of linked subunit nAChRs appear similar to those of nAChRs expressed from traditional monomer constructs, suggesting that linking does not significantly distort receptor structure: linked and unlinked receptors differed by only about 30% in  $EC_{50}$  and were identical in their response to the competitive antagonist trimetaphan, indicating that their binding site is very similar. These results compare well with those obtained by Sigel and co-workers in their expression of GABA<sub>A</sub> receptors by combining trimer and dimer constructs (Baumann *et al.*, 2002).

Multimeric constructs for nicotinic superfamily receptors will allow us to produce receptors with a specified composition and subunit topology. This is particularly important for neuronal nAChRs and for GABA<sub>A</sub> receptors, because these channels can exist in a number of possible combinations of subunit isoforms (Colquhoun *et al.*, 2003; Whiting, 2003) and, in the case of neuronal nAChRs, also in different  $\alpha:\beta$  stoichiometries (Nelson *et al.*, 2003). Being able to obtain and characterise pure receptor populations with predefined subunit stoichiometry or composition will aid in dissecting them out *in vivo*. Pentameric constructs are likely to be useful also in the clarifying the open question of the subunit stoichiometry of heteromeric glycine receptors (Kuhse *et al.*, 1993; Burzomato *et al.*, 2003; Grudzinska *et al.*, 2005).

Another important experimental route opened by concatamer techniques is the possibility to introduce a defined number of mutations in subunits present in multiple copies in a receptor and to choose the location of such mutations. Being able to introduce single mutation copies in such receptors is important in order to understand how

channelopathies with autosomal dominant inheritance produce their phenotype in heterozygotes. In addition, one of the reasons for testing the pentamer-construct approach was that it could be better than lower-order concatemers at producing defined mutant receptors when dealing with homomeric receptors, such as some glycine receptors and  $\alpha 7$  neuronal nAChRs. This is an important point for future work.

As an example of the power of this approach, we tested the effect of introducing single copies of the 9' L to T mutation in the second transmembrane domain of the  $\alpha$  or the  $\beta$  subunit. While the effects of each copy of the mutation appear to add (on log scale, as was assumed in our work with monomer constructs (Boorman *et al.*, 2000)), being able to mutate one subunit at a time shows that the effects of the mutation are much bigger when it is carried by an  $\alpha$  subunit.

In conclusion, we demonstrated the feasibility of expressing pentameric constructs for neuronal nAChRs. The pharmacology of these linked receptors is similar to that of receptors expressed by the conventional monomer technique. These full-length linked receptors do not appear to suffer from the problems of lower-order concatamers such as breakdown in the linker or faulty incomplete incorporation of the linked subunits (Nicke *et al.*, 2003; Groot-Kormelink *et al.*, 2004).

This powerful technique can in principle be used for any receptor in the nicotinic superfamily and could be extended to any of the channels that have been studied with lower-order concatamers (Minier and Sigel, 2004) and this will allow for the first time

the expression of defined subunit complexes, formed by a planned subunit combination and topology and containing the desired number of mutations in the desired location.

## References

- Baumann SW, Baur R and Sigel E (2001) Subunit arrangement of  $\gamma$ -aminobutyric acid type A receptors. *J Biol Chem* **276**:36275-36280.
- Baumann SW, Baur R and Sigel E (2002) Forced subunit assembly in  $\alpha 1\beta 2\gamma 2$  GABA<sub>A</sub> receptors. INSIGHT INTO THE ABSOLUTE ARRANGEMENT. *J Biol Chem* **277**: 46020-46025.
- Baumann SW, Baur R and Sigel E (2003) Individual properties of the two functional agonist sites in GABA<sub>A</sub> receptors. *J Neurosci* **23**:11158-11166.
- Boorman JP, Beato M, Groot-Kormelink P J, Broadbent S D and Sivilotti L G (2003) The effects of  $\beta 3$  subunit incorporation on the pharmacology and single channel properties of oocyte-expressed human  $\alpha 3\beta 4$  neuronal nicotinic receptors. *J Biol Chem* **278**:44033-44040.
- Boorman JP, Groot-Kormelink P J and Sivilotti L G (2000) Stoichiometry of human recombinant neuronal nicotinic receptors containing the  $\beta 3$  subunit expressed in *Xenopus* oocytes. *J Physiol (Lond)* **529**:567-578.
- Burzomato V, Groot-Kormelink P J, Sivilotti L G and Beato M (2003) Stoichiometry of recombinant heteromeric glycine receptors revealed by a pore-lining region point mutation. *Recept Chann* **9**:353-361.
- Colquhoun D, Unwin N, Shelley C, Hatton C J and Sivilotti L (2003) Nicotinic acetylcholine receptors, in *Burger's Medicinal Chemistry and Drug Discovery*:

*Fundamentals of Medicinal Chemistry* (Abraham D ed) pp 357-405, John Wiley & Sons Inc, New York.

Conroy WG and Berg D K (1995) Neurons can maintain multiple classes of nicotinic receptors distinguished by different subunit compositions. *J Biol Chem* **270**:4424-4431.

Forsayeth JR and Kobrin E (1997) Formation of oligomers containing the  $\beta 3$  and  $\beta 4$  subunits of the rat nicotinic receptor. *J Neurosci* **17**:1531-1538.

Groot-Kormelink PJ, Broadbent S D, Boorman J P and Sivilotti L G (2004) Incomplete incorporation of tandem subunits in recombinant neuronal nicotinic receptors. *J Gen Physiol* **123**:697-708.

Grosman C and Auerbach A (2000) Asymmetric and independent contribution of the second transmembrane segment 12' residues to diliganded gating of acetylcholine receptor channels: a single-channel study with choline as the agonist. *J Gen Physiol* **115**:637-651.

Grudzinska J, Schemm R, Haeger S, Nicke A, Schmalzing G, Betz H and Laube B (2005) The  $\beta$  subunit determines the ligand binding properties of synaptic glycine receptors. *Neuron* **45**:727-739.

Hoenderop JG, Voets T, Hoefs S, Weidema F, Prenen J, Nilius B and Bindels R J (2003) Homo- and heterotetrameric architecture of the epithelial  $\text{Ca}^{2+}$  channels TRPV5 and TRPV6. *EMBO J* **22**:776-785.

Im WB, Pregenzer J F, Binder J A, Dillon G H and Alberts G L (1995) Chloride channel expression with the tandem construct of  $\alpha 6$ - $\beta 2$  GABA<sub>A</sub> receptor subunit requires a monomeric subunit of  $\alpha 6$  or  $\gamma 2$ . *J Biol Chem* **270**:26063-26066.

Kuhse J, Laube B, Magalei D and Betz H (1993) Assembly of the inhibitory glycine receptor: identification of amino acid sequence motifs governing subunit stoichiometry. *Neuron* **11**:1049-1056.

Labarca C, Nowak M W, Zhang H, Tang L, Deshpande P and Lester H A (1995) Channel gating governed symmetrically by conserved leucine residues in the M2 domain of nicotinic receptors. *Nature* **376**:514-516.

Liman ER, Tytgat J and Hess P (1992) Subunit stoichiometry of a mammalian K<sup>+</sup> channel determined by construction of multimeric cDNAs. *Neuron* **9**:861-871.

Minier F and Sigel E (2004) Techniques: Use of concatenated subunits for the study of ligand-gated ion channels. *Trends Pharmacol Sci* **25**:499-503.

Moretti M, Vailati S, Zoli M, Lippi G, Riganti L, Longhi R, Viegi A, Clementi F and Gotti C (2004) Nicotinic acetylcholine receptor subtypes expression during rat retina development and their regulation by visual experience. *Mol Pharmacol* **66**:85-96.

Nelson ME, Kuryatov A, Choi C H, Zhou Y and Lindstrom J (2003) Alternate stoichiometries of  $\alpha 4\beta 2$  nicotinic acetylcholine receptors. *Mol Pharmacol* **63**:332-341.

Nicke A, Rettinger J and Schmalzing G (2003) Monomeric and dimeric byproducts are the principal functional elements of higher order P2X<sub>1</sub> concatamers. *Mol Pharmacol* **63**:243-252.

Stoop R, Thomas S, Rassendren F, Kawashima E, Buell G, Surprenant A and North R A (1999) Contribution of individual subunits to the multimeric P2X<sub>2</sub> receptor: estimates based on methanethiosulfonate block at T336C. *Mol Pharmacol* **56**:973-981.

Whiting PJ (2003) GABA-A receptor subtypes in the brain: a paradigm for CNS drug discovery? *Drug Discov Today* **8**:445-450.

Zhou Y, Nelson M E, Kuryatov A, Choi C, Cooper J and Lindstrom J (2003) Human  $\alpha 4\beta 2$  acetylcholine receptors formed from linked subunits. *J Neurosci* **23**:9004-9015.

Zwart R and Vijverberg H P (1998) Four pharmacologically distinct subtypes of  $\alpha 4\beta 2$  nicotinic acetylcholine receptor expressed in *Xenopus laevis* oocytes. *Mol Pharmacol* **54**:1124-1131.



***Footnotes***

This work was supported by the Wellcome Trust (project grant 064652), by a Medical Research Council postgraduate scholarship (to SB) and by a Medical Research Council Special Research Training Fellowship in Bioinformatics/Neuroinformatics (to MB).

Reprint requests to Lucia Sivilotti, Dept. of Pharmacology, University College London, Gower Street, London, WC1E 6BT, U.K; e-mail [l.sivilotti@ucl.ac.uk](mailto:l.sivilotti@ucl.ac.uk)

### ***Legends for Figures***

**Figure 1**  $\alpha 3\beta 4$  neuronal nicotinic receptors expressed from the pentameric construct have ACh sensitivity similar to that of receptors expressed from monomeric constructs (**a, b**) examples of current responses elicited by increasing ACh concentrations on the two types of receptors

(**c**) concentration-response curves for  $\alpha 3 + \beta 4$  (monomeric) receptors and for the  $\alpha 3 + \beta 4$  (pentameric) receptors ( $n = 4$  and  $6$ , respectively). Lines are fits of the data with the Hill equation.

All responses were recorded from *Xenopus* oocytes voltage clamped at  $-70$  mV in nominally 0-calcium solution.

**Figure 2** RNA gel-electrophoresis of capped cRNA constructs used for *Xenopus laevis* oocyte injections. Approximately  $1\text{ }\mu\text{g}$  of  $\alpha 3$  (1),  $\beta 4$  (2),  $\beta 4\_ \alpha 3^{\text{LT}}$  tandem (3),  $\alpha 3^{\text{LT}}$  (4),  $\beta 4^{\text{LT}}$  (5),  $\beta 4\_ \beta 4\_ \alpha 3\_ \beta 4\_ \alpha 3$  penta (6),  $\beta 4^{\text{LT}}\_ \beta 4\_ \alpha 3\_ \beta 4\_ \alpha 3$  mutant penta (7),  $\beta 4\_ \beta 4\_ \alpha 3\_ \beta 4\_ \alpha 3^{\text{LT}}$  mutant penta (8), and  $\beta 4^{\text{LT}}\_ \beta 4\_ \alpha 3\_ \beta 4\_ \alpha 3^{\text{LT}}$  mutant penta (9) were separated on a 1.5% agarose-gel. The 0.24-9.5 Kb RNA ladder is indicated on the left.

The predicted cRNA sizes are; 1.8 kb for  $\alpha 3$  and  $\beta 4$  monomers, 3.4 kb for  $\beta 4\_ \alpha 3$  tandem, and 8 kb for the pentameric constructs.

**Figure 3** Expression of an excess of  $\alpha 3^{\text{LT}}$  or  $\beta 4^{\text{LT}}$  together with the pentamer construct does not result in incorporation of the mutant monomers into functional receptors.

Example traces (**a** and **b**, left-hand side) give an estimate of the extent of the functional excess of monomer subunit cRNA injected by showing that the same quantity of

monomer cRNA produced very large functional response if co-expressed with the appropriate monomer.

The concentration response curves obtained from receptors expressed after co-injection of mutant monomer with wild-type pentamer constructs (full circles and continuous lines,  $n = 4$  for both) are identical with those obtained after expression of wild-type pentamer alone (dashed curves).

**Figure 4** Non-equivalent effects of L9'T mutations inserted in the second transmembrane domain of a single  $\alpha$  or a single  $\beta$  subunit.

(a) Example current responses elicited by increasing concentrations of ACh.

(b, c) Comparison of the concentration-response relation for pentamer-expressed receptors bearing an L9'T mutation on a single  $\alpha$  subunit ( $\beta_4\text{-}\beta_4\text{-}\alpha_3\text{-}\beta_4\text{-}\alpha_3^{\text{LT}}$ ), a single  $\beta$  subunit ( $\beta_4^{\text{LT}}\text{-}\beta_4\text{-}\alpha_3\text{-}\beta_4\text{-}\alpha_3$ ) or both ( $\beta_4^{\text{LT}}\text{-}\beta_4\text{-}\alpha_3\text{-}\beta_4\text{-}\alpha_3^{\text{LT}}$ ).

Note that the increase in agonist sensitivity produced by a single mutation copy is greater if the mutation is in  $\alpha$  (filled triangles,  $n = 4$ ). This single-mutation shift is greater than the approximately 6-fold shift expected from previous experiments in which all  $\alpha$  or all  $\beta$  were mutated (shown for reference by the dotted line, Boorman *et al.*, 2000).

Conversely, the increase in ACh sensitivity is less than expected when the mutation is inserted in  $\beta$  (filled circles,  $n = 5$ ).

When the two mutations are combined, their effects sum (on the logarithmic scale, i.e. the shifts multiply), as shown by the bottom plot (filled squares, continuous line,  $n = 4$ ), where the dotted line is the 36-fold shift expected on the basis of the previous data (Boorman *et al.*, 2000).

Figure 1

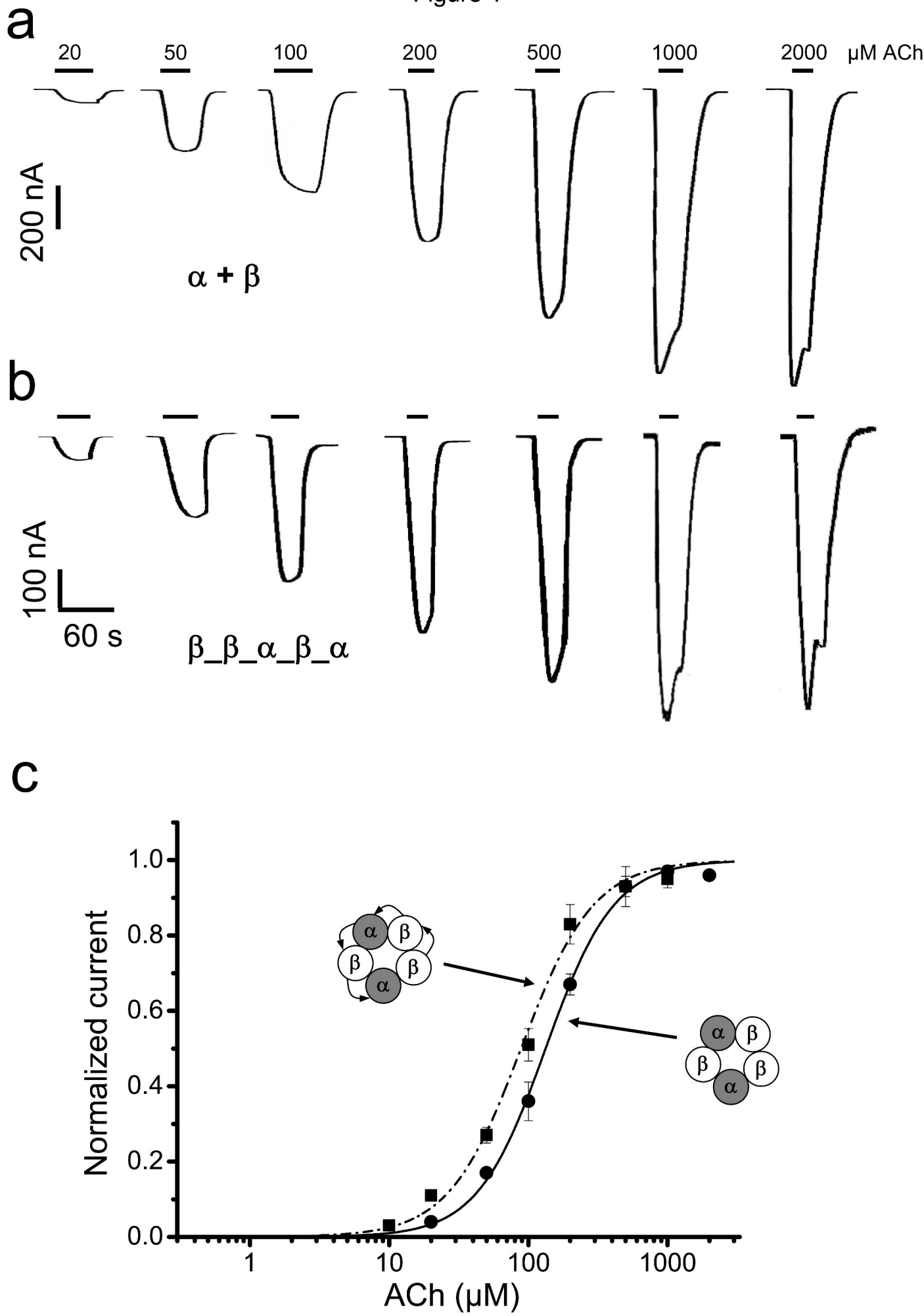


Figure 2

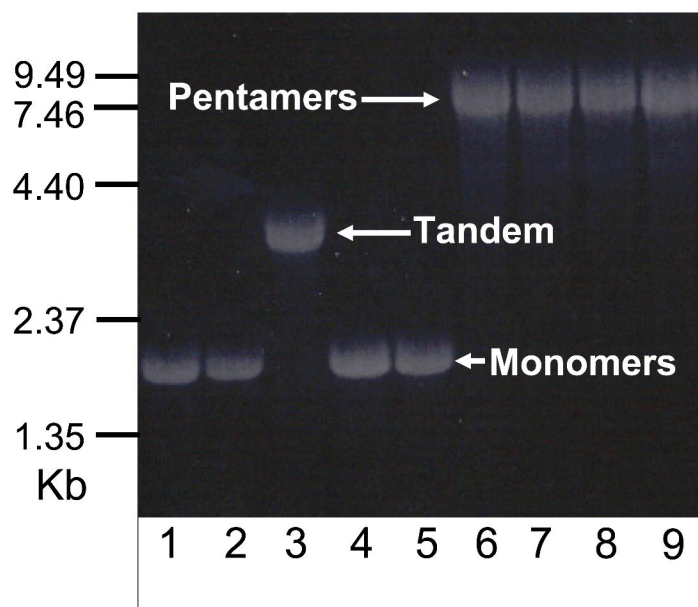
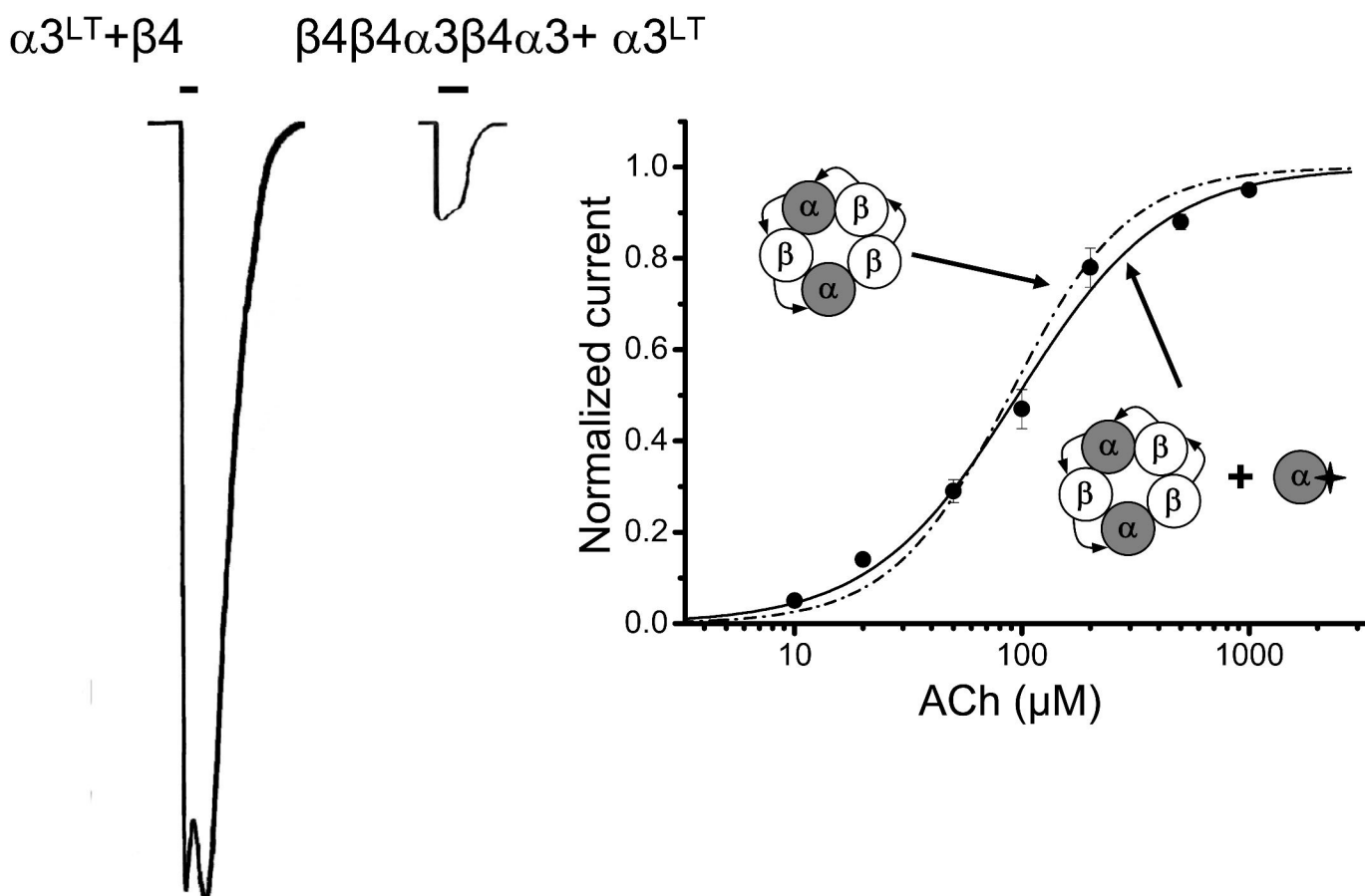


Figure 3

**a**



**b**

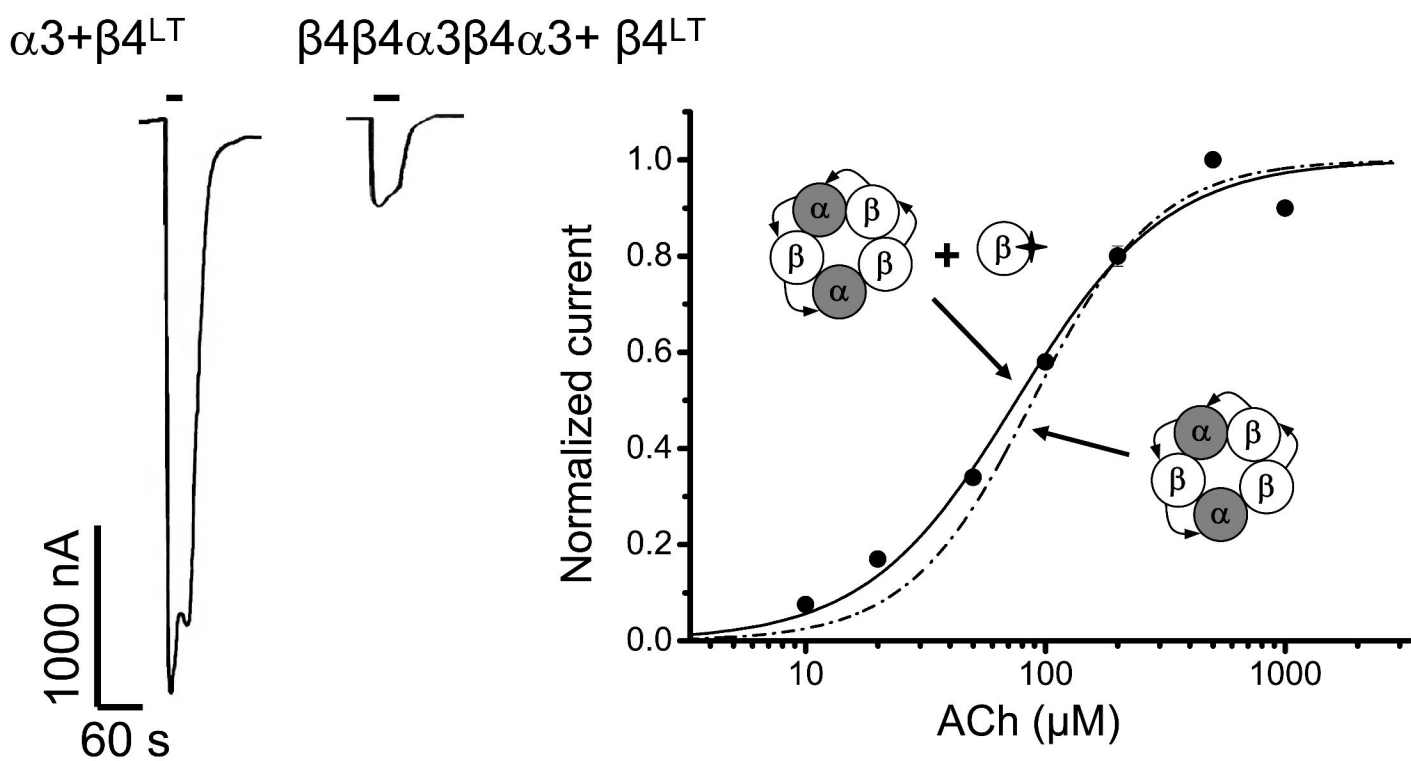
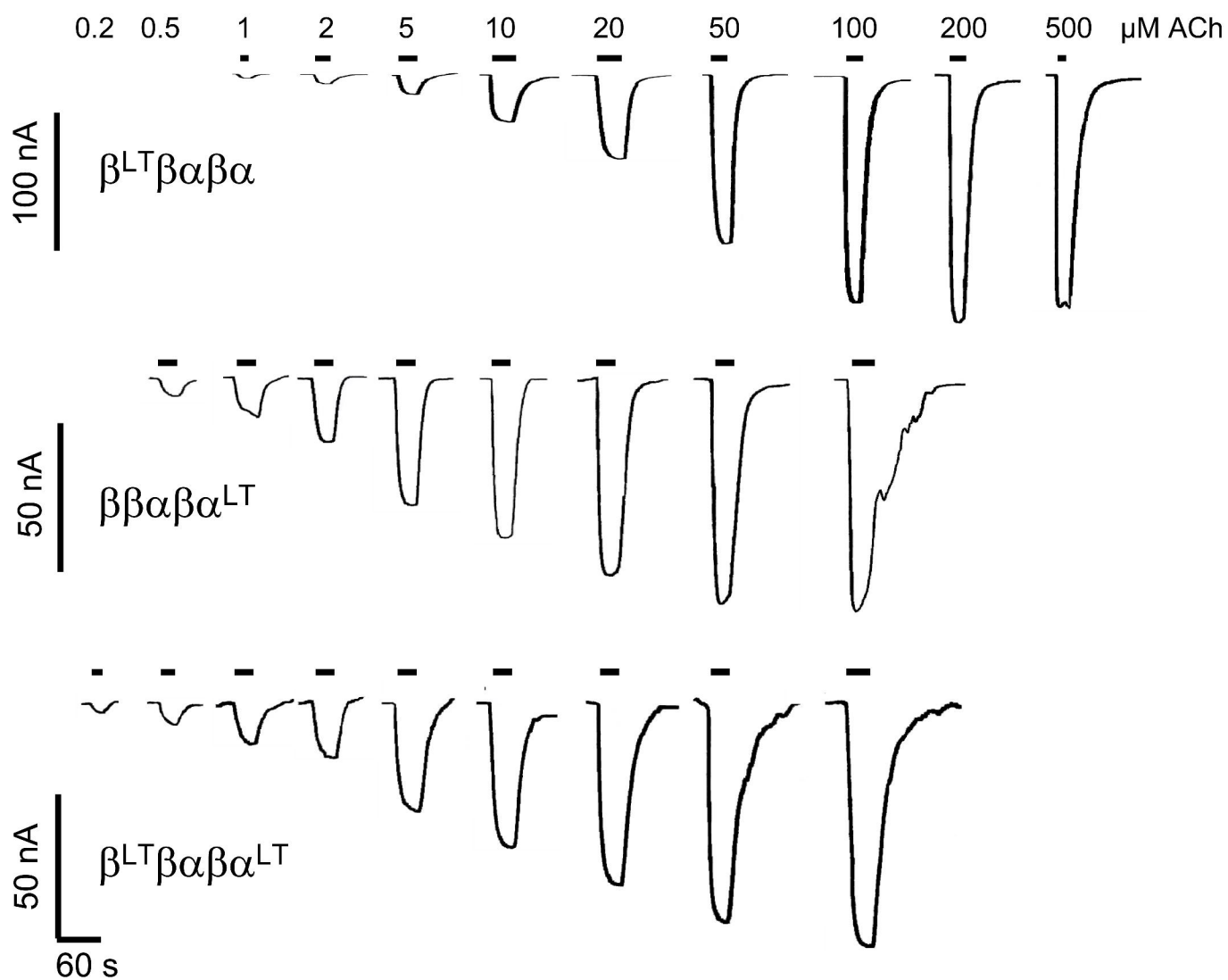
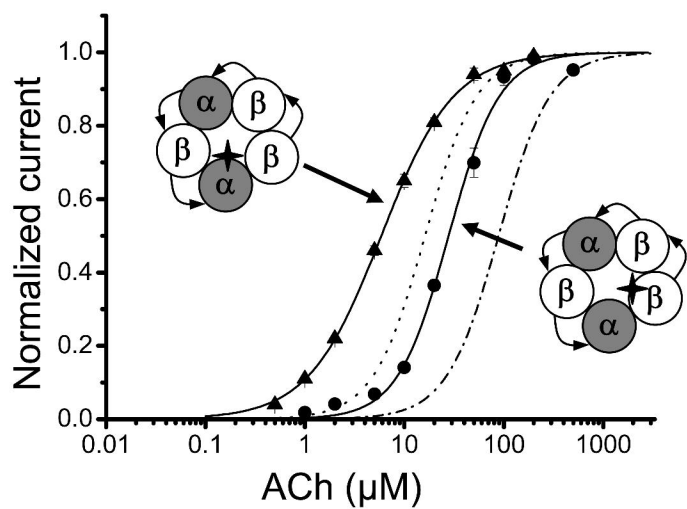


Figure 4

**a****b****c**