3\textsubscript{10} helices in channels and other membrane proteins

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The very large number of protein structures currently available has revealed that long 3\textsubscript{10} helices are present in proteins. A 1999 survey found 132 cases of 3\textsubscript{10} helices with six amino acids or more (Pal and Basu, 1999). More recently, a structural analysis of 689 protein chains with low sequence identity (≤20\%) and solved at better than 1.6-Å resolution found 1,774 3\textsubscript{10} helices spanning five residues or more (Enkhbayar et al., 2006). As expected, the large majority was composed of helices with fewer than two helical turns, but a significant number spanned more than seven residues: 53 helices were 8 residues long, 13 helices were 9 residues long, 4 helices spanned 10 residues, and 1 helix was 11 residues long. This study also classified individual 3\textsubscript{10} helices as regular or irregular, according to the level of variation of stereochemical parameters along the helix, and found that the percentage of irregular helices increased rapidly with length. Interestingly, the authors concluded that 3\textsubscript{10} helices are para-helices, helices where long-range order is not maintained.

Clearly, the stability of a helix in a protein structure is very dependent on the packing interactions established with other protein regions. For α helix packing in
proteins, it has been shown that there is a maximization of the interaction surface between helices (Bowie, 1997). In an α helix, the 3.6 residues per turn positions side chains every 100° around the helical axis, staggering the side chains and offering an extensive set of modes of interaction (Fig. 1). This arrangement therefore imposes few structural restrictions on the interacting partners and increases the probability of the stabilization of long α helices in a protein. In contrast, as a result of the ~3.2 residues per helical turn in 3_10 helices, side chains are disposed in a more restrictive fashion; they form ridges along the helix (Fig. 1). Intuitively, this disposition imposes specific structural requirements for the packing of long 3_10 helices with other protein regions. In an effort to verify this idea, we performed a visual inspection of long 3_10 helices containing at least two turns (seven or more residues) in protein structures listed in three different papers (Peters et al., 1996; Pal and Basu, 1999; Enkhbayar et al., 2006). These reports only name a small fraction of the structures included in their studies. As a result, the final pool contained 12 proteins for a total of 13 helices (Protein Data Bank accession nos. and residues in helices are listed in the legend of Fig. 2). We found two modes of packing. Mode A was observed in eight cases. In this mode, a side-chain ridge lies in a groove formed by other regions of the protein (example in Fig. 2 A). Mode B was present in four helices. In this arrangement, one or two side chains from another region of the protein pack against the 3_10 helix face formed between the side-chain ridges (example in Fig. 2 B). A single case was observed where the helix is completely encased by the rest of the protein; this helix has a very specific sequence with four glycines and one proline out of eight residues. More quantitatively, the different modes are distinguishable by the fraction of solvent-exposed surface area, such that helices lying in a groove (mode A) tend to be less solvent exposed than in the other packing arrangement (mode B; Fig. 2 C). Overall, this simple analysis supports the idea that packing of long 3_10 helices has specific requirements. It also highlights the need for more extensive studies of the structural context in which 3_10 helices are found. We suggest that long 3_10 helices are rarely observed in protein structures, not just because they might be intrinsically less stable than α helices but also because they have packing requirements that are rarely met over long extensions, resulting in the unraveling of the 3_10 conformation or in the variability of the helical stereochemical parameters detected in many studies.

Another important characteristic of 3_10 helices is dynamics. This property has been well documented in isolated peptides, which are important model systems for the study of helices. In the case of 3_10 helices, one of the best-studied systems involves peptides rich in α methylalanine, a non-natural amino acid with an extra methyl group on the α carbon (Karle and Balaram, 1990; Karle et al., 1994; Crisma et al., 2006; Bellanda et al., 2007). Because of the stereochemical constraints imposed by the presence of two large substituents in the Cα of the amino acid, these peptides have a strong tendency to adopt a helical conformation, 3_10 or α helical. In these systems, it has been demonstrated that a peptide can adopt both conformations and that it is possible to shift the equilibrium between one conformation and the other by altering the polarity of the solvent or temperature. In some cases, these two conformations appear to coexist in the same peptide so that one region adopts a 3_10-helical conformation and another region adopts an α-helical conformation. A few similar observations have been documented for peptides formed by natural amino acids; the two conformations appear to be present in different segments of the peptide, and this distribution is altered by small sequence changes (Fiori et al., 1994; Dike and Cowsik, 2006; Mikhonin and Asher, 2006). Molecular dynamics studies of helices in peptides have also proposed that 3_10 and α helices coexist along the same peptide and that interconversion between the two

![Canonical α-helix and Canonical 3(10) helix](figure1.png)

**Figure 1.** Canonical helical conformations. Side views and views along the axes of a helix in a canonical α-helical conformation (left) and canonical 3_10 conformation (right). Dotted lines indicate hydrogen bonds between atoms in the backbone of polypeptide. Helices were generated using PepBuild. All figures were prepared with PYMOL.

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conformations occurs rapidly in the nanosecond time-scale (Tirado-Rives and Jorgensen, 1991; Chipot and Pohorille, 1998; Raman et al., 2008). Interestingly, the presence of main-chain bifurcated hydrogen bonds, where residue \( i \) is simultaneously hydrogen bonded to \( i+3 \) and \( i+4 \), has been detected by molecular dynamics (Armen et al., 2003).

310 helices in potassium channels

Long 310 helices have been described in the crystal structures of three potassium channels: the bacterial cyclic nucleotide–regulated potassium channel (MlotiK1) (Clayton et al., 2008) and the human Kv1.2 (Long et al., 2005a,b)- and Kv2.1-chimeric (Long et al., 2007) voltage-gated potassium channels. All of these channels belong to the superfamily of six-TM helix tetrameric cation channels and share the same three-dimensional architecture (Fig. 3 A).

In the structures of the Kv1.2- and Kv2.1-chimeric voltage-gated channels, the fourth TM helix (S4) adopts a 310-helical conformation over 7 and 10 residues, respectively. In these channels, S4 is the voltage sensor, a functionally important region with a conserved sequence motif \((R_i,xxR_i,xxR_i,xxR_i,xxR_i,xxR_i,xxR_i,xxR_i,xxR_i,xxR_i)\), where every third residue is positively charged (usually \( R_1 \) to \( R_6 \) are arginines, and \( K_6 \) is a lysine), and \( x \)'s are large hydrophobic residues. S4 together with three other TM helices, S1, S2, and S3, forms the voltage sensor domain (Fig. 3 A). It has been well established that \( R_1 \) to \( R_6 \) are the charges that sense the membrane electrical field (Aggarwal and MacKinnon, 1996; Seoh et al., 1996). In the Kv2.1-chimeric channel, solved at 2.4 Å, the 310 conformation stretches from \( R_1 \) to \( R_6 \), and the side chains of all charged residues in this stretch are buried within the rest of the voltage sensor domain (Fig. 3 B), forming salt bridges with negatively charged residues from S2 and S3. Residues \( R_i \), which happens to be a glutamine in this channel, and \( K_6 \) are in a \( \alpha \)-helical region and are partially exposed to the surrounding environment, probably corresponding to the hydrophilic groups of the phospholipid bilayer. In the Kv1.2 channel structure (Fig. 3 C), a recent re-refinement establishes that the 310 conformation extends from \( R_1 \) to \( R_6 \), with the positively charged side chains in this stretch buried within the rest of the voltage sensor domain and shielded from the lipidic environment (Chen et al., 2010). These structures confirm the early suggestions of the presence of a 310 conformation in the S4 of voltage-gated channels (Noda et al., 1984).

As a result of the voltage-gate channel structures, a role for the 310-helical conformation in voltage sensing has been proposed (Long et al., 2007; Clayton et al., 2008). It is widely accepted that the voltage-sensing mechanism involves translation of S4 across some part of the membrane; most likely, this translational movement is accompanied by a rotation, and some have suggested that S4 rotates along its axis (Tombola et al., 2006; Swartz, 2008). The details and extension of these movements are still a matter of discussion, but the 310-helical conformation offers an apparently simple explanation for some of the issues raised by the properties of S4.
Among these issues are: (a) the energetic cost of having positively charged residues translating through the low dielectric constant environment of the membrane, (b) the mechanistic basis behind the highly conserved sequence in S4, and (c) the mechanism of rotation of S4. First, the presence of the $\beta_{10}$ helix places many of the positively charged side chains at every third position on the same face, buried within the voltage sensor domain and shielded from the lipid environment. Therefore, the $\beta_{10}$ conformation solves issues (a) and (b) because if S4 were to adopt a totally $\alpha$-helical conformation, some of the positively charged residues would necessarily be on the lipid apolar regions. Second, the conversion between the $\beta_{10}$ and $\alpha$-helical conformations observed in peptides, and described above, effectively results in a rotation of residues, and it provides a mechanistic model for issue (c). It has therefore been proposed that the transition between the $\beta_{10}$ and $\alpha$-helical conformations occurs during voltage sensing and that it is this movement that shields the positively charged residues away from the lipid environment. It is possible that as shown in peptides, the conversion (rotation) is restricted to a fraction of the TM helix.

Several functional studies have recently explored or included the $\beta_{10}$ conformation of S4 as a component of voltage sensing. Villalba-Galea et al. (2008) have modeled the functional behavior of S4 in voltage sensor domains with three different states, resting, activated, and relaxed, in which transition from resting or activated to the relaxed state corresponded to a conversion between a $\beta_{10}$ and an $\alpha$ helix. In a voltage-gated sodium channel, cysteine cross-linking experiments between residues in S4 and residues in other helices of the voltage sensor have been interpreted with a model that includes the $\beta_{10}$ conformation (DeCaen et al., 2009). A recent report (Xu et al., 2010) of a minimal voltage sensor reinforces the functional importance of the S4 sequence periodicity (RxxR) and its implications for maintaining the $\beta_{10}$ conformation. Computational studies of voltage-gated channels have observed conversion of S4 between $\alpha$- and $\beta_{10}$-helical conformations, either during simulation of a channel in the resting state (Khalili-Argha et al., 2010) or during simulation of the effects of membrane hyperpolarization in an activated-state channel (Bjelkamar et al., 2009).

In many of the studies considering the $\beta_{10}$ conformation as a component of voltage sensing, it has been proposed that shielding of the positively charged residues away from the apolar regions of the lipid/detergent phase is the major factor in the stabilization of the long $\beta_{10}$ helices. However, two other structures, those of the MlotiK1 channel (Clayton et al., 2008) and of the voltage sensor domain of the KvAP channel (Jiang et al., 2003), strongly suggest that the groove formed by S1, S2, and S3 also plays a role in the stability of the $\beta_{10}$ conformation. MlotiK1 is a ligand-gated channel (Fig. 3 A) where opening and closing of the pore is induced by the binding of cyclic nucleotides to a C-terminal cytoplasmic domain (Clayton et al., 2004; Nimigean et al., 2004). In MlotiK1, S4 lacks the crucial R1, R2, R3, and R4 and is thought not to function as a voltage sensor. Importantly, S4 adopts a $\beta_{10}$-helical conformation over a stretch of 11 amino acids, none of which are positively charged residues (Fig. 3 D). This observation demonstrates that the shielding of charged residues is not the only factor that stabilizes the $\beta_{10}$ conformation. Comparison of the structure of the voltage sensor domain from the K2.1-chimeric channel with the structure of the S1–S4 domain from MlotiK1 offers some clues about the stabilization of the $\beta_{10}$ helix in these channels. In these domains, S1, S2, and S3 form a groove where S4 fits (Fig. 3, B–D).

Figure 3. Domain architecture of six-TM channels. (A) Extracellular view of MlotiK1 structure, a bacterial cyclic nucleotide–regulated potassium channel, representative of the superfamily of six-TM helix cation channels. Subunits are shown in different colors. S1 to S4 compose the S1–S4 domain (structurally equivalent to a voltage sensor domain), and S5 and S6 (a pair from each subunit) form the pore domain. The voltage sensor domains of (B) Kv2.1-chimeric voltage-gated potassium channel and of (C) Kv1.2 voltage-gated potassium channel are shown in more detail. (D) The S1–S4 domain of the MlotiK1 channel. Surface representations correspond to S1, S2, and S3. Helices S4 are shown as a thin helical trace along $\alpha$-helical segments and as a thick ribbon along $\beta_{10}$ stretches. Conserved positively charged residues, as well as MlotiK1 proline-108, are shown in stick model. The domains are oriented with the extracellular regions at the top of figure and cytoplasmic regions at the bottom. The N termini of S4 are on the extracellular side of the domains.
In MlotiK1, the whole length of S4 lies in a fairly straight groove and the $3_{10}$ becomes an $\alpha$ helix just before proline-108 in the helix, which ruptures the main-chain hydrogen-bonding network and appears to distort the helix (Fig. 3 D). In contrast, in the Kv2.1-chimeric channel the groove is not as extensive, disappearing on the extracellular half of the TM domain (Figs. 4 A and 3 B). Transition from the $3_{10}$ to the $\alpha$-helical conformation occurs around the region where the groove disappears and S4 is no longer tightly packed within the rest of the domain. In both channels, the $3_{10}$ helix coincides with the regions in S4 that are embedded within the groove formed by the other helices, just like in one of the $3_{10}$ packing modes described above.

The structure of the voltage sensor domain from the bacterial voltage-gated KvAP channel also provides clues about stabilization of $3_{10}$ helices in these channels. This structure comprises the helices S1–S4 crystallized in complex with a monoclonal antibody; the channel’s pore domain is missing (Jiang et al., 2003). S4 has a partial voltage sensor sequence that includes the crucial first four positively charged residues with canonical spacing (R1xxR2xxR3xxR-lxx). Interestingly, this S4 does not adopt a $3_{10}$ conformation; it is all $\alpha$ helical. Superposition with the voltage sensor domain from the Kv2.1-chimeric channel reveals a very high degree of structural similarity (Fig. 4 B); however, the groove formed by S1, S2, and S3 in KvAP is much wider and shallower, and the $\alpha$-helical S4 is no longer enveloped by the other helices in the domain. It is easy to conceive that S4 also adopts a $3_{10}$ conformation in the native KvAP channel. It is possible that truncation of the voltage sensor domain and/or binding of the antibody may have caused a rearrangement of the structure, leading to a change in the packing of S4 and the unwinding of its $3_{10}$ conformation. Regardless of what happens in the native KvAP structure, the comparison between the KvAP, MlotiK1, and Kv2.1-chimeric structures leads back to the idea we raised above, that the $3_{10}$ conformation has specific packing arrangements for its long-range stability (Fig. 4 C). In the structures of the voltage sensor/S1–S4 domains, the long helices packed in an almost parallel fashion create a groove that appears to be important for the stabilization of the $3_{10}$ conformation in S4.

$3_{10}$ helices in membrane proteins

The observation of long $3_{10}$ helices in three potassium channels raises the possibility that other membrane proteins also have long $3_{10}$ helices. We analyzed $\sim$233 structures of $\alpha$-helical TM proteins that are deposited in the Protein Data Bank and catalogued in database maintained by the laboratory of Stephen White (White, 2004). To avoid low quality structures and structures of the same protein in different states, we reduced this already relatively small universe to a group of structures with nonredundant sequences at 3.2-Å resolution or better. Making use of the secondary structure analysis, which is associated with each coordinate file in the Protein Data Bank, we selected only the structures that contain $3_{10}$ helices with five residues or more and that have these $3_{10}$ helices positioned within their membrane-associated region, that is, either buried within the bilayer or positioned very close to the...
membrane surface. We found 25 structures for a total of 31 helices. Among these, we found 19 helices that are 5 residues long, 3 helices with 6 residues, 3 helices with 7 residues, and 3 helices with 8 residues; we also found 1 helix for each of following lengths: 9, 10, and 11 residues. The final group included the MlotiK1 and the Kv2.1-chimeric channels but not the Kv1.2 channel because of its close sequence relationship with the Kv2.1-chimeric channel. To compare our results with the previous analysis performed on soluble proteins (Enkhbayar et al., 2006), we calculated the frequency of helices for each length within the universe of helices with five residues or more, and plotted the results in Fig. 5 A. Within the clear limitations of our analysis, it is striking that for membrane proteins, 40% of the \( \beta \) helices identified were longer than five residues, whereas in soluble proteins, this number was significantly smaller, just 20%. The higher frequency of long \( \beta \) helices in membrane proteins is also clear when looking at defined helix lengths with seven or more residues. More structures are needed, but these results suggest that long \( \beta \) helices are more prevalent in membrane proteins relative to soluble proteins. Strikingly, visual inspection of the \( \beta \) helices in some of these membrane proteins reveals several interesting situations (Fig. 5, B–D): in cytochrome bc(1) complex (Protein Data Bank accession no. 2FYU), a \( \beta \) helix with eight residues lies in a groove formed by the other TMs and is in close proximity to a heme, although not in direct contact with it; in the bacterial nitrate reductase A (Protein Data Bank accession no. 1Q16), a seven-residue-long \( \beta \) helix directly coordinates the metal ion of a heme through a histidine side chain. The helix is packed between the heme and a phosphatidyl glycerol molecule; in the cyanobacterial photosystem II complex (Protein Data Bank accession no. 3BZ1), an eight-residue-long \( \beta \) helix lies on top of a layer formed solely by lipids, chlorophyll A, and \( \beta \) carotene molecules, where it fits within a groove.

\[ \text{Figure 5.} \ \beta \text{ helices in other membrane proteins.} \ \text{(A) Graph comparing the frequency of} \ \beta \text{ helices in soluble and in membrane proteins. Only} \ \beta \text{ helices with lengths between 5 and 11 residues have been considered. The number of helices in each length category was normalized to the total number of detected helices with five or more residues. Inset shows in more detail the differences between membrane and soluble proteins for helices longer than six residues. The data for} \ \beta \text{ helices from soluble proteins has been extracted from Enkhbayar et al. (2006). Examples of} \ \beta \text{ helices in membrane proteins:} \ \beta \text{ helices are shown in red, other protein regions are shown as a blue ribbon, and prosthetic groups are shown as CPK spheres, unless otherwise indicated.} \ \text{(B) } \beta \text{ helix in cytochrome bcI complex (Protein Data Bank accession no. 1FYU). Protoporphyrin IX containing Fe (heme) is shown in close proximity to the helix.} \ \text{(C) In bacterial nitrate reductase A (Protein Data Bank accession no. 1Q16), the iron atom from the heme is coordinated by histidine (yellow CPK spheres) from the} \ \beta \text{ helix. Opposite the heme and on the top side of the figure, there is phosphatidyl glycerol molecule completing the packing of the} \ \beta \text{ helix.} \ \text{(D) In the cyanobacterial photosystem II complex (Protein Data Bank accession no. 3BZ1), a} \ \beta \text{ helix is found embedded in a layer formed by LMG (1,2-distearoyl-monogalactosyl-di} \ \text{glyceride),} \ \beta \text{ carotene, and chlorophyll A.} \]
All of these examples raise interesting questions about the role of $3_{10}$ helices in these proteins: Do $3_{10}$ helices play structural and/or functional roles in these proteins? Do different protein functional states correspond to an interconversion between a $3_{10}$ and $\alpha$-helical conformation?

In conclusion, the structural and functional properties of long $3_{10}$ helices in proteins are still largely unexplored. For example, the sequence and structural context of these helices still need to be carefully analyzed. Further, the examples of long $3_{10}$ helices in membrane proteins and in particular in channels reveal potential functional roles that are just being unveiled and that will be the catalyst for many interesting experiments.

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