Peptide carrier potentiality of *Bacillus subtilis* levansucrase

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A synthetic oligodeoxynucleotide encoding the vasopressin peptide was ligated to the 3' terminal codon of sacB, the structural gene of levansucrase. This gene fusion was integrated into the chromosome of a *Bacillus subtilis* strain able to overproduce levansucrase. The extracellular production of the hybrid protein, consisting of the whole levansucrase primary sequence plus the nine amino acids of the vasopressin peptide added at the C-terminal end, represented 50-55% of that found for the wild-type levansucrase (20 mg l⁻¹). The purified hybrid protein displayed the same conformational stability, protease insensitivity and enzymic properties as the wild-type levansucrase. However, the rate and the yield of the unfolding-folding transition at the pH and temperature used for bacterial growth were lower in the case of the hybrid protein; the latter also required a higher iron concentration to be completely folded.

Introduction

Levansucrase is one of the few proteins secreted by *B. subtilis* during the exponential growth phase (Dedonder, 1966). The expression of its structural gene, sacB, requires induction by sucrose and is regulated by a number of genes (Lepesant et al., 1976). Among them, sacU is of particular interest since sacU strains secrete levansucrase in large quantities, about 8% of total protein and the only one released into the culture medium during the exponential phase of growth (Chambert & Petit-Glatron, 1984). These properties make the expression/secretion signals of sacB particularly attractive for the construction of secretion vectors (Wong, 1989). However, attempts to translocate normally intracellular prokaryotic proteins or extracellular eukaryotic proteins by fusing their genes to the sacB signal sequence have so far failed (Dion et al., 1989), the secretion block occurring at the post-translational level (Sarvas, 1986).

Such results were not in our view surprising since we concluded (Chambert & Petit-Glatron, 1990), from an extensive investigation of its secretion mechanism, that the tertiary structure flexibility of mature levansucrase plays a key role in its secretion process. We proposed that the newly synthesized protein remains in an unfolded state which is essential for insertion into the membrane. The acquisition of the folded state of the protein, catalysed by metal ions such as Fe³⁺ or Ca²⁺ whose intracellular levels are low (Norris et al., 1991), occurs on the external side of the membrane and is tightly coupled with its release into the external medium. It would therefore appear difficult to engineer a foreign protein for secretion through the same pathway as levansucrase. If, on the other hand, levansucrase secretion is strongly dependent upon its intrinsic folding properties, this protein could be of value as a carrier for foreign peptides which have little effect on such properties.

The approach of peptide secretion via the expression of gene fusions has been recently developed with different envelope proteins in *Escherichia coli* (Charbit, 1991), but is poorly developed in *B. subtilis*. One of the reasons for the latter is the proteolytic degradation of hybrid proteins expressed during the later phases of growth (Ulmanen et al., 1985). However, since proteases are only weakly expressed during exponential growth (Kunst et al., 1974), levansucrase–peptide hybrids should provide model systems with which to gain further insight into the mechanism of the translocation process of levansucrase. We have chosen the levansucrase–vasopressin fusion as a model system to investigate. Vasopressin is a nonapeptide that contributes very little to the net charge and hydrophobicity of levansucrase. It contains an intramolecular disulphide bond which may be expected to direct its self-governing folding independently of the protein-carrier. We have focused our attention both on the secretion efficiency of this hybrid and on the folding properties of its purified extracellular form.
Methods

Purification of extracellular levansucrases. Wild-type and hybrid levansucrases were prepared from culture supernatants of the induced B. subtilis strains GM9150 and GM9151, respectively, according to the published procedure (Dedonder, 1966).

Levansucrase assay. Levansucrase activities were estimated by measuring the initial rate of the fructosyl exchange reaction and of fructosyl polymerase activity (Chambert & Gonzy-Tréboul, 1976; Chambert & Petit-Glatron, 1989).

Pulse-labelling experiments. Cells of B. subtilis were pulse-labelled with [35S]methionine as described previously (Chambert & Petit-Glatron, 1988).

Gel electrophoresis and immunoblotting. Proteins were analysed on 10% (w/v) SDS polyacrylamide gels. Electrophoresis was performed using a slab-gel apparatus with the discontinuous system described by Laemmli (1970). Immunoblotting on nitrocellulose sheets (0-45 μm pore size), in 25 mM-Tris/HCl pH 8-3, 192 mM-glycine, 20% (v/v) methanol and 0-42% SDS, was carried out using a constant current of 400 mA for 2 h. Incubation with purified rabbit anti-levansucrase antibodies and radio-iodinated Protein A was as described previously (Petit-Glatron et al., 1987).

Preparation and purification of antibodies. Antibodies against pure extracellular levansucrase were raised in rabbits. Levansucrase was covalently coupled to glutaraldehyde-activated ultrogel (Act Ultrogel ACA, Pharmacia) and the antibodies purified by affinity chromatography (Avrameas & Ternynck, 1969).

Unfolding and refolding experiments. The unfolding–refolding transitions of levansucrase were monitored using changes either in intrinsic fluorescence measured with a F2000 Hitachi thermoregulated spectrofluorimeter or in resistance to proteolytic degradation (Chambert et al., 1990).

Culture and strains. Strains were grown at 37 °C in the following minimal medium: 0-1 m-potassium phosphate pH 7, 25 mM-(NH4)2SO4, 0-5 mM-MgSO4, 0-01 mM-MnSO4, 22 μg ferric ammonium citrate ml−1 (60 μM Fe2+), 0-1 mM-glucose. B. subtilis QB112 (sacA32, sacB) was used as a host strain for the integration of DNA fragments containing the gene fusion or sacB wild-type gene. B. subtilis QB112 was transformed by the procedure of Anagnostopoulou & Spizizen (1961). Transformants were selected on LB plates supplemented with kanamycin (10 μg ml−1) or chloramphenicol (5 μg ml−1). B. subtilis strains GM9150 and GM9151 were constructed for this work.

E. coli XLI-B was used as a host for plasmid propagation as described previously (Chambert & Petit-Glatron, 1991).

Plasmids. The amplified DNA fragment was cloned into the BamHI and XhoI sites of pBluescript plasmid. The XhoI end of the DNA fragment was repaired to flush end with the Klenow fragment of DNA polymerase I and deoxynucleotide triphosphates before ligation into the EcoRV site of pGEM5. Plasmid pGEM5 was obtained by insertion of the kanamycin-resistance gene cassette purified from pBEST502 (Itoya et al., 1989) into the PstI site of plasmid p LS50 (Steinmetz et al., 1985), indicated by an asterisk in Fig. 1(a). After digestion of pLS50 with PstI and ligation with the kanamycin-resistance gene cassette, transformants were selected on plates containing ampicillin and kanamycin.

In vitro construction of the gene fusion. The nucleotide sequence of vasopressin was fused in-frame to the C-terminal codon of the sacB gene using a synthetic oligonucleotide including this sequence as a primer for the polymerase chain reaction (PCR). The codons used for the nucleotide sequence of the hormonal peptide were chosen from the 'optimal' B. subtilis codons as defined by Sharp et al. (1990).

The first primer, 5'-dCCGCTCGAGTTACGTAGATTTGGTTACACGGGCGGCCTTTGTTAACTGTTATTTGTCC-3', corresponds to nucleotides 169–190 of the published sequence of the sacB region. The second primer, 5'-dCCTCGAG

Results

Construction of a B. subtilis strain containing the gene fusion as a single copy in the chromosome

The fusion gene coding for the levansucrase–vasopressin hybrid (sacBV) was ligated into the BamHI and EcoRV sites of pGEM5 after the XhoI end had been repaired to form a blunt end. The resulting plasmid, pGEM5, was used to transform strain QB112. Transformants in which the DNA fragments were integrated into the chromosome by double crossing-over events between two homologous sequences, as indicated in Fig. 1(b), were selected for their kanamycin (Km) resistance and chloramphenicol (Cm) sensitivity. About 10% of the KmR transformants were found to be CmS. A similar construction was carried out with pGEM5 to provide a reference strain for wild-type levansucrase production. The resulting B. subtilis strains were called GM9151 and GM9150, respectively.

Production of levansucrase–vasopressin hybrid

Extracellular production of the hybrid protein by strain GM9151 was compared with that of the wild-type levansucrase by strain GM9150 (Fig. 2a). Quantitative analysis of immunoblots showed that the proteins exhibited the expected size difference (approximately 1 kDa) and that the major part of both proteins (>80%) was released in a homogeneous form (Fig. 2b). Production of the hybrid protein, at 1-9 μg ml−1 per OD650 unit, was about half that of the wild-type levansucrase at 3-6 μg ml−1 per OD650 unit.

Kinetics of levansucrase secretion in both strains were studied by pulse-chase experiments (not shown). The total amount of hybrid protein produced by strain GM9151 represented approximately 55% of the labelled levansucrase released by strain GM9150 and both proteins displayed the same stability in the culture supernatant. In both cases, they were the only proteins secreted into the culture medium.
Purification and enzymic properties of the levansucrase–vasopressin hybrid

Purification of the hybrid protein was achieved by chromatography on hydroxyapatite. This protein displayed the same chromatographic behaviour as the wild-type protein and eluted at 1.1 M-potassium phosphate pH 6. Stock solutions of 1 mg ml⁻¹ of the purified hybrid protein in 0.1 M-potassium phosphate pH 6 were prepared for further characterization and could be stored at −20 °C for several weeks without apparent loss of enzyme activity.

The kinetic parameters of the reaction of levan synthesis from sucrose were evaluated at 25 °C for both proteins (Chambert & Petit-Glatron, 1989). Both enzymes had the same $k_{cat}$ (2.5 ± 0.3 × 10⁴ min⁻¹); however, the values of $K_m$ for sucrose were slightly different – 3.6 ± 0.6 × 10⁻² M for wild-type levansucrase and 7 ± 1.6 × 10⁻² M for the hybrid protein. The fact that the hybrid protein displayed similar chromatographic and enzymic properties to those of wild-type levansucrase suggested that the elongation at the carboxyl terminus had a rather small effect on the final tertiary conformation of hybrid levansucrase–vasopressin.

Conformational stability of the hybrid protein under bacterial growth conditions

In the pulse-chase experiments described above we showed that wild-type levansucrase and the hybrid protein remained stable in the culture supernatant during the experiments. A more precise estimation of the
Fig. 2. Comparison of production of levansucrase and levansucrase–vasopressin hybrid by B. subtilis strains GM9150 and GM9151. (a) Extracellular release of proteins was measured by quantitative immunoblotting. The arrow indicates the beginning of the induction promoted by the addition of 50 mM-sucrose. ○, GM9150; ●, GM9151. (b) Electrophoresis on 10% (w/v) SDS polyacrylamide gel and immunoblotting analysis of the extracellular medium and the bacterial pellet of induced strains GM9150 and GM9151 grown to an OD_{600} of 4. Lanes 2 and 5: 10 μL of cell supernatant of GM9151 and GM9150, respectively. Lanes 3 and 6: 60 μL of cell supernatant of GM9151 and GM9150, respectively. Lanes 4 and 7: 60 μL of cell pellet of GM9151 and GM9150, respectively, resuspended in the initial volume and sonicated before analysis. Lane 1 contains 50 ng of purified levansucrase as a control.

respective stabilities under such conditions can be obtained from the determination of the free energy of unfolding \( \Delta G_D \) for each protein. The curves of denaturation by urea were therefore established by exposing each protein to various concentrations of this denaturant at the same pH (7.0), temperature (37 °C) and salt composition as that used for bacterial growth. The change in proteinase sensitivity occurring under these conditions allowed us to analyse the urea-induced unfolding process (Chambert et al., 1990). The free energies of unfolding for each protein are represented as a function of urea concentration in Fig. 3, according to Pace's plot (Pace, 1986). The values of \( \Delta G_D^{30} \) obtained by extrapolation to zero urea concentration were estimated as \( \Delta G_D^{30} = 2300 \pm 200 \text{ cal mol}^{-1} \) and \( \Delta G_D^{30} = 1700 \pm 200 \text{ cal mol}^{-1} \) for the wild-type levansucrase and the hybrid protein, respectively [1 cal = 4184 J]. This means that the protein elongation slightly decreases the overall stability of levansucrase, the native extracellular hybrid protein being protease-resistant under the pH and temperature conditions of bacterial growth.

Kinetics of the unfolding–refolding transition of the levansucrase–vasopressin hybrid mediated at pH 7 and 37 °C

The kinetics of unfolding–refolding transition were compared for both proteins under two different conditions (Chambert et al., 1990).

First, denaturation of both proteins was performed in 0.1 M-potassium acetate buffer, pH 7, in the presence of EDTA. The refolding was then promoted by the addition of Ca^{2+}. Under such conditions, changes in intrinsic fluorescence intensity provided a suitable method for monitoring the unfolding–refolding transition. Traces of fluorescence intensity changes (Fig. 4) showed that both proteins were rapidly denatured in the presence of 0.1 mM-EDTA. After addition of 50 mM-Ca^{2+} to the solution of the denatured form, 90% and 50% of the fluorescence properties of the native forms were
Secretion of a levansucrase–vasopressin hybrid

Fig. 4. Unfolding–refolding transition of wild-type levansucrase (A) and levansucrase–vasopressin hybrid (B) mediated by Ca$^{2+}$ at 37°C, pH 7, measured by intrinsic fluorescence intensity changes. Traces represent fluorescence intensity as a function of time (excitation wavelength 285 nm, emission wavelength 336 nm). Aliquots (7.5 μl) of the stock solutions of the purified proteins (1 mg ml$^{-1}$) were mixed (arrow 1) with 1 ml 0.1 M-potassium acetate pH 7 containing 0.1 mM-EDTA and preincubated at 37°C. After 1 min of unfolding, refolding was initiated by the addition of 50 μl 1 M-CaCl$_2$ in 0.1 M-potassium acetate pH 7 (arrow 2).

recovered in the case of wild-type levansucrase and the hybrid protein, respectively. Assuming a simple two-state model for the unfolding–refolding transition, the relaxation time, $\tau$, for each event and for each protein could be calculated by using the equation $(I_0 - I) = (I_\infty - I_0) e^{-t/\tau}$, where $I_0$, $I_\infty$, and $I$ are the values of fluorescence intensity at any time, zero time and infinite time, respectively, of the unfolding or the refolding process. These estimations gave the same value for unfolding, $\tau_u = 29 \pm 1$ s, but different ones for refolding, $\tau_r = 104 \pm 2$ s and 179 ± 6 s for wild-type levansucrase and the hybrid protein, respectively.

Secondly, both proteins were denatured by 8 M-urea and then their refolding initiated by diluting this denaturing agent with buffer containing the same salt concentrations as the growth medium. The unfolding–refolding transitions were followed by monitoring the appearance of resistance to proteolytic degradation. As shown in Fig. 5, the recovery of protease resistance was 70% for the wild-type levansucrase and only 30% for the hybrid protein. Moreover, the initial rate of refolding was lower for this latter protein. In the presence of a tenfold concentration of ferric ions in the renaturation buffer, we observed a greater increase of the yield of refolding for the hybrid protein than for the wild-type levansucrase.

The results obtained from both approaches allowed us to conclude that the extension of the levansucrase polypeptide chain alters both the rate and the yield of correct refolding under the conditions of temperature and pH used for its production from *B. subtilis*.

**Endoproteinase treatment of the hybrid protein**

When this work was initiated, it was postulated that vasopressin could direct its self-governing folding independently of the carrier levansucrase. It might therefore have been expected that the peptide bond between the two parts of the fusion protein would display a particular sensitivity to hydrolysis by proteinases. Endoproteinase Lys-C was therefore used to attempt to digest the hybrid protein, since the peptide bond involves the carbonyl group of the terminal lysine of levansucrase. As shown in Fig. 6, the hydrolysis of the hybrid protein did not release the carrier levansucrase. It was therefore concluded that our first hypothesis was not correct and the insertion of a recognition sequence for a restriction protease between levansucrase and the piloted peptide would be necessary to exploit levansucrase as a potential peptide carrier.
the energy used for the vectorial diffusion of the protein folding could be important for an efficient coupling of accompanying folding. However, we proposed from an analysis of the reaction mixture were withdrawn at intervals, mixed with 100 µl 50 mM-ammonium bicarbonate buffer pH 8, at 25 °C. Aliquots (40 µl) of the electrophoresis sample buffer (containing 2% SDS) and analysed by Laemmli (1970). Lanes: A, levansucrase (8 pg); B, hybrid protein (8 µg); C, a mixture of levansucrase and hybrid protein (8 µg each); D, E, and F, kinetics of hybrid protein digestion by proteinase, 1, 5 and 60 min, respectively.

Discussion

The model we have proposed (Chambert & Petit-Glatron, 1990) for levansucrase release in B. subtilis emphasized the key role of the polypeptide chain flexibility and the modulation of the folding rate by metal ions such as Ca²⁺ and Fe³⁺. It has been recently postulated that α-amylase, another enzyme of B. subtilis, is also subject to conformational changes during its secretion process (Kontinen et al., 1991).

The results obtained here with the levansucrase-vasopressin hybrid protein strengthen the hypothesis of a tight coupling between the efficiency of secretion and subsequently correct folding catalysed by metal ions such as Fe³⁺ and Ca²⁺. We have postulated (Chambert et al., 1990), as others have done (Eilers & Schatz, 1988), that the energy used for the vectorial diffusion of the protein through the membrane is provided by the energy change accompanying folding. However, we proposed from an irreversible thermodynamic point of view that the rate of folding could be important for an efficient coupling of these two processes. This hypothesis is supported by this work, since the decrease of the secretion yield of the hybrid may be correlated with a lower rate of unfolding–folding transition and a lower yield of correct refolding compared with wild-type levansucrase.

It has been pointed out repeatedly that proteolytic degradation of heterologous or hybrid proteins is one of the major obstacles to the use of B. subtilis as producer of secreted proteins (Henner, 1990). It appears from this work that in the case of levansucrase such an obstacle may be overestimated since our hybrid protein remains protease-insensitive in the extracellular medium. However, it was shown that the rate of correct protein folding is fundamental for a high yield of secreted protein recovery. Identification in the mature levansucrase of sites playing a critical role in the folding event, particularly potential metal-binding domains, would be essential to a further understanding of the process. From previous genetic analyses (Lepesant et al., 1976) various mutants of B. subtilis producing levansucrase altered both in its secretion and in its conformational stability have been isolated. Studies of these sacB alleles are presently in progress in our laboratory. Such an approach could give us a rational way to study the peptide carrier potentialities of levansucrase.

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References


