

Intrinsic protein disorder could be overlooked in cocrystallization conditions - An SRCD case study

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Abstract: X-ray diffractometry dominates protein studies, as it can provide 3D structures of these diverse macromolecules or their molecular complexes with interacting partners: substrates, inhibitors and/or cofactors. Here we show that under cocrystallization conditions the results could reflect induced protein folds instead of the (partially) disordered original structures. The analysis of synchrotron radiation circular dichroism spectra revealed that the Im7 immunity protein stabilizes the native-like solution structure of unfolded NColE7 nuclease mutants via complex formation. This is consistent with the fact that among the several available crystal structures with its inhibitor or substrate, all NColE7 structures are virtually the same. Our results draw attention to the possible structural consequence of protein modifications, which is often hidden by compensational effects of intermolecular interactions. The growing evidence on the importance of protein intrinsic disorder thus, demands more extensive complementary experiments in solution phase with the unligated form of the protein of interest.

Keywords: induced protein folding; SRCD spectroscopy; colicin E7 nuclease; Im7 immunity protein

50-75-word statement, written for a broader audience:

So far, all the 11 crystal structures of WT and mutant NColE7 suggested that this protein has a stable structure not influenced by modifications. Using SRCD spectroscopy we demonstrate that a disorder does occur upon certain mutations, and the native-like structure can be induced by inhibitor binding. This case study gives insight into how the structural disorder may get hidden in experimental conditions involving a mutant protein and its interacting partners.

Introduction

Studies on colicin nucleases revealed that an intrinsic disorder might be induced by mutations of the enzymes.¹⁻³ In independent parallel research, published recently, it was shown that certain properties of such colicin E3 and E7 mutants can be fully restored by protein–protein interactions.^{2,4} Colicin E7, the nuclease toxin of *Escherichia coli*, is a particular example of this kind⁵⁻⁸ as its nuclease domain (NColE7) has been extensively studied by X-ray crystallography. The C-terminal HNH active centre is made up of ~ 40 amino acids forming a $\beta\beta\alpha$ -type Zn^{2+} -ion binding structure.⁹⁻¹¹ Similar HNH motifs¹²⁻¹⁵ are observed in various endonucleases, such as the homing¹⁶, restriction¹⁷, or nonspecific enzymes¹⁸. While this motif in NColE7 binds to the 3' site of the scissile phosphodiester-group in the DNA minor groove, the central helical regions also form strong nonspecific interactions in the major groove.^{14,19-22} The ~ 40 amino acids long N-terminal sequence is known to have no well-defined secondary structure and to contain an Arg, which is necessary for effective nuclease activity.²³⁻²⁶ In addition, the N-terminus was also found to affect the structure of the enzyme. Controlling of a conserved metal binding catalytic motif through an intramolecular allosteric activation by a distal part of the protein is an intriguing mechanism in protein research. Therefore, to get a more profound view of the role of these residues, we designed eight variants of NColE7 (Fig. 1), including N-terminal truncated mutants, missing 4, 25, 45 or 69 amino acid residues,²⁴ as well as, point mutants substituting the (T454) threonine and/or (K458) lysine and/or (W464) tryptophan amino acid with alanines.^{1,2}

Fig. 1. – near here

Molecular recognition is a key issue in function of the colicin nucleases. The Im7 immunity protein is needed to prevent the cleavage of nucleic acids by NColE7 in *E. coli* cells

during protein expression. The four antiparallel α -helices of Im7²⁷ strongly and specifically interact with the nucleic acid binding helical regions of NCoIE7,^{15,28} based on charge and surface-complementarity.²⁹⁻³¹ This as well as the interaction with the substrate DNA may affect the structure of NCoIE7 mutants. In the crystal structures published so far, NCoIE7 and its mutants are present together with either Im7^{13,15,16,29} or DNA,^{15,21,22,27} with the exception of only two crystals: the Zn²⁺-complexes of NCoIE7 itself²⁰ and its Δ N4 truncated mutant.³² Independently of the interacting molecules or ions, the overall nuclease structure is retained in all crystals. Despite the detailed crystallographic information available, there is a limited knowledge on the solution structure of this protein. This inspired us to investigate the structural consequences of the interaction of mutant NCoIE7 proteins (shown in Fig. 1) with Im7 in aqueous solution in more detail. In this study, we show how the folding of NCoIE7 is induced by specific protein–protein interactions using synchrotron radiation circular dichroism spectroscopy. The possible discrepancies between solution and crystallographic protein structure studies, caused by such induced structures are also discussed.

Results

The interaction of Im7 with NCoIE7 has minor consequences on the protein structure both in crystal and in solution phases

Comparing the crystal structures of the free and complexed NCoIE7 and Im7 proteins,^{15,27,28} suggests that neither of the native proteins undergo significant structural changes in their complexes [Fig. 2(A)]. The superimposition of the free NCoIE7 structure (1M08¹⁵) and the Im7 bound NCoIE7 structure (7CEI²⁸) revealed very few differences and the RMSD is 0.408 for 109 C α atoms. Likewise, the free Im7 protein (1CEI²⁷) is very similar to the NCoIE7 bound Im7 protein, with an RMSD value of 0.414 for 76 C α atoms.

Fig. 2. – near here

SRCD spectra of the free NCoIE7 and Im7 proteins and their mixture have been recorded to verify that the above statement holds also in solution phase. NCoIE7 and Im7 display far-UV SRCD spectra in correspondence with the structures being rich in α -helices [Fig. 2(B), 2(C)], as observed in the crystalline state for both proteins. The experimentally obtained and the mathematical sum of the individual spectra are indeed very similar. The small differences between the protein spectra obtained in the presence and absence of metal ion may be related both to structural adjustment and to charge transfer transitions in the UV region arising from complexation with the Zn^{2+} -ion. No interaction was detected between Im7 and Zn^{2+} (data not shown).

The SRCD spectra of NCoIE7 and Im7 proteins were subjected to evaluation of the secondary structure element composition by various programs. The results are collected in Table I, together with the calculations based on the difference spectra derived from the protein mixtures as well as from the crystal structures of the two proteins. Even the relative amounts of the secondary structure elements obtained from the crystal structure differ according to the applied algorithm, as shown e.g. for the 1M08¹⁵ structure in the table. The alterations in the results obtained by various programs can be attributed to the different classifications of the secondary structure elements by the authors. The comparison of the results calculated with the same program, however, provides the same trends.

Table I. – near here

Interactions of NColE7 and its N-terminal mutants with the Im7 protein in bacteria

According to *in vitro* DNA cleavage assays, the nuclease activity of the mutant proteins containing single (W464A), double (K458A/W464A) or triple (T454A/K458A/W464A) amino acid changes (all including W464A mutation) drastically decreased in comparison to the wild-type enzyme or to the TK point mutant (T454A/K458A) in which W464 was not affected. Nevertheless, all the point mutants remained cytotoxic: the coexpression of Im7 was necessary for their production, demonstrating their mutual interaction with the inhibitor.^{1,2}

In contrast, the N-terminally truncated NColE7 mutants all could be overexpressed without the coexpression of Im7.^{24,25} The Im7 binding of the latter proteins was therefore, studied *in vitro*. The genes of each NColE7 mutant were also constructed to express a GST (glutathione-S-transferase) fusion protein together with Im7. Then, GST pull-down assays with the N-terminally truncated NColE7 mutants were carried out in the presence of Im7 protein. Figure 3 shows that all mutants were able to interact with Im7, except for the shortest Δ N69-NColE7 protein, although the latter still contains the intact Im7 binding region.

Fig. 3. – near here

Correlation between the Im7 and the DNA binding of NColE7 mutants

The inhibitor and the substrate bind to overlapping regions of NColE7. Therefore, the comparison of these interactions provides information on the relative binding affinity of Im7 and DNA. The DNA binding of the TKW point mutant and N-terminally truncated NColE7 proteins have been determined previously by gel mobility shift assays.^{1,2,24,25} The point mutant and the Δ N4-NColE7 truncated protein showed almost the same affinity towards DNA as NColE7, but the shorter proteins gradually lost their DNA binding ability. It is intriguing that the Δ N45-NColE7 protein could not bind DNA,²⁴ but it bound Im7. This phenomenon

was further studied using a sensitive method, such as the flow linear dichroism (FLD) spectroscopy. FLD of a double-stranded CT-DNA sample yields a characteristic negative signal at the absorbance maximum of the DNA bases (*ca.* 260 nm) since the transition moments of the base $\pi \rightarrow \pi^*$ transitions are located in the plane of the bases, and these are oriented orthogonally with respect to the orientational axis of DNA double helix.³³ Although the nuclease activity was completely suppressed by the addition of EDTA, a large impact of small amounts of NCoIE7 on DNA LD signal was observed due to DNA-binding. In contrast, the addition of Δ N45-NCoIE7 did not affect the FLD spectrum of the DNA (Fig. 4), supporting the previous observations by gel electrophoresis.²⁴

Fig. 4. – near here

The difference in the Im7- and DNA-binding features of Δ N45-NCoIE7 raised the question, whether a structural activation can occur in this severely truncated, partially disordered NCoIE7 variant upon the binding to Im7.

Im7-binding alters the solution structure of the intrinsically disordered NCoIE7 point mutants

Previously we have shown that several N-terminal NCoIE7 mutants have distinct features from NCoIE7. Among the T454A and/or K458A and/or W464A NCoIE7 mutants, those including the latter point mutation undergo severe structural changes in aqueous solutions according to their SRCD spectra. In the series of the NCoIE7, TK, TKW, KW and W mutants, two distinct types of spectra were identified: the first two proteins showed the same native-like spectral pattern, while the last three resulted in spectra characteristic for proteins with a large fraction of unordered structure.^{1,2}

Fig. 5. – near here

Figure 5 shows the effect of the interaction with the Im7 protein on the spectrum of the TKW mutant. It is clear that the solution structure of the mutant (similarly to those of TW and W mutants – not shown) is recovered by binding of the Im7 protein, since the experimental SRCD spectrum of the TKW/Im7 complex is identical to that of the NCoIE7/Im7 complex, while the mathematical sum of the TKW and Im7 component spectra – assuming that no interaction occurs in the solution – differs significantly both in the intensity and spectral pattern.

N-terminally truncated variants of NCoIE7 and their interaction with Im7

The four N-terminal amino acids (446-KR NK-449) are required for catalytic activity of NCoIE7.^{25,26} However, they do not affect the overall fold of the protein in the crystal structure.³² The truncation including these amino acids does not have significant effect on the DNA and Zn²⁺-binding properties, as well.²⁵ On the other hand, the deletion of longer amino acid strings from the N-terminus in Δ N25, Δ N45 and Δ N69-NCoIE7 mutants gradually abolishes the ability for Zn²⁺ and DNA binding, and even the Im7 binding capability is lost in the latter protein (see Fig. 3).

The shape and intensity of the mean residue molar SRCD spectra of the Δ N25, Δ N45-NCoIE7 truncated mutants significantly differ from that of the native NCoIE7 [Fig. 6(A)]. The decrease of the spectral intensity suggests a decrease of the helical content, as it is supported by the calculated secondary structure distributions (Table II). This is, however, against expectations considering that sequences of mainly unordered structure were deleted in the truncated mutants, while the amino acid residues comprising the central helical region

remained intact. This indicates that the N-terminal sequence of NCoIE7 consisting of ~40 amino acids stabilizes the NCoIE7 structure, in agreement with the observations on the effect of the W464A point mutation within this region.

Fig. 6. – near here

Table II. – near here

As shown in Figure 6(B), there is only a slight difference between the experimental SRCD spectra of the Δ N45-NCoIE7 mutant obtained in the presence and absence of Im7. Thus, while this mutant does bind Im7, it does not refold, suggesting that the binding to Im7 occurs through the numerous (14) positively charged side chains in the interacting region with partially helical structure. It is likely that this interaction occurs without extending the structure stabilization effect to the rest of the protein.

At the same time, the spectra of Δ N25-NCoIE7 clearly demonstrate the significant structural change caused by its interaction with Im7, as the measured spectrum of the protein–protein complex differs from the mathematical sum of the protein component spectra [Fig. 6(C)].

Discussion

Solution structure of native NCoIE7

Circular dichroism spectroscopy is a useful tool to obtain rough information about the solution structure of proteins by evaluation the spectra concerning the secondary structure elements. Independently of the programs applied,³⁴⁻³⁹ our calculations revealed slightly decreased helical content and overestimated amounts of turns for NCoIE7, or turns and β -strands for Im7 in comparison to the crystal structures (Table I). This may be attributed to the

uncertainty of the analysis of secondary structure distribution. As there is no crystal structure available for the apo NCoIE7, we performed solution studies to reveal whether the metal ion binding had any influence on the NCoIE7 SRCD spectra. No significant differences were observed compared to the apo protein – in contrary to the dramatic structural change of the zinc finger proteins with similar $\beta\beta\alpha$ -metal ion binding motif upon removal of the Zn^{2+} -ions.⁴⁰⁻⁴²

In case there is no structural change upon protein-protein interaction, the intensities of individual CD signals are additive. This is predicted for NCoIE7–Im7 complex by the available crystal structures. Therefore, it is possible to analyse the difference spectra obtained by subtraction of the spectral contribution of one component from the experimental curve of the mixture. The results of such calculations revealed slight changes in the secondary structure distribution of both NCoIE7 and Im7 proteins (Table I). The mutual stabilization of the more flexible protein regions can be the reason for the slight increase of the fraction of the β -sheet and decrease in the fraction of unordered structure of either NCoIE7 or Im7, in contrast to the crystal data.

Mutations of NCoIE7 result in structural changes

Since there are numerous crystal structures on NCoIE7 reporting that the structure of the various mutants in complex with Im7 or DNA are all virtually the same, it was surprising to observe significant structural changes upon N-terminal modifications. An intriguing property of NCoIE7 is that while its active centre is situated at the C-terminus, the N-terminus also influences the catalytic activity, even though it is located on the surface of the protein, and is not directly involved in the formation of well defined secondary structure elements. The structural changes caused by the mutations within the N-terminal sequence led us to the recognition of an important feature of this protein: the native-like structure of partially

disordered mutants can be induced by binding to its substrate or to its inhibitor protein. Table III shows the summary of the Im7 and DNA binding properties, as well as the cytotoxic and *in vitro* catalytic activity of the point mutant and N-terminally truncated NCoIE7 proteins (Fig. 1). These data demonstrate that the gradual removal amino acids from the N-terminus abolished the nuclease activity first in the Δ N4-NCoIE7 mutant,²⁵ then the DNA binding affinity decreased for the Δ N25-NCoIE7 mutant.²⁵ The Δ N45-NCoIE7 mutant already could not interact with DNA²⁴ as also confirmed by the flow linear dichroism method here (Fig. 4). In contrast, Δ N45-NCoIE7 could still bind Im7 (Fig. 3). These observations accord with the stronger interaction of NCoIE7 with the inhibitory protein than with the substrate DNA. In order to reveal the structural consequences of this interaction, maintained even in the severely truncated disordered mutant, we studied the Im7-binding by SRCD spectroscopy in detail.

Table III – near here

Im7 binding induces the folding of the truncated mutants

The Zn²⁺-binding site of NCoIE7 is preorganized² thus, a change in the affinity for the metal ion indicates severe conformational changes in the C-terminal HNH-motif. The decreased metal binding affinity by the N-terminal truncation in Δ N25, Δ N45 and Δ N69-NCoIE7 mutants suggest that a part of the protein structure is altered. Indeed, the analysis of the CD spectra of both the Δ N25 and Δ N45-NCoIE7 truncated mutants [Fig. 6(A)] revealed an increased disorder in the structure compared to the expected one, based on the intact NCoIE7 structure (Tables I and II).

The structure of Im7 is unaffected by the interaction with NCoIE7. Therefore, we supposed that any significant changes in the CD spectra of the Im7 complexes of NCoIE7 mutants can be attributed to the induced folding of the nucleases. Thus, to calculate the

changes in the secondary structure we subtracted the spectrum of Im7 from the spectra of its complexes with the truncated mutants and analyzed the difference spectra assigned to the latter proteins. The secondary structure distribution of the truncated proteins shown in Figure 7, revealed that the structures are at least partially – Δ N25-NCole7 to a larger, and Δ N45-NCole7 to a lesser extent – refolded due to the interaction with the immunity protein.

Fig. 7. – near here

Notably, the W464 residue belongs to the deleted amino acid sequences in Δ N25 and Δ N45-NCole7. W464 (together with F499, W500, L509, F513) is a key residue in forming the hydrophobic core of the protein. These interactions are extended towards the N-terminal chain (L465, P475, V476, P477) and also the HNH motif (V563).³² The disturbance of this hydrophobic patch results in severe structural consequences.

Structural activation as reflected by metal binding

The analysis of the SRCD spectra of the point mutants revealed a drastically decreased fraction of the ordered secondary structures upon W464A mutation. Typically, the fractions of the secondary elements calculated by the CDPro program package³⁸ comprise 16% α -helix 22% β -sheet, 21% turn and 41% of unordered sequence, while BeStSel³⁵ provides 11% α -helix 20% β -sheet, 18% turn and 51% of unordered sequence for these proteins. The changes in the structure mirror the significantly decreased metal ion binding affinity of these mutants,² which was shown to be recovered in their Im7 complexes possessing a native-like SRCD spectral pattern (Fig. 5). Although the SRCD spectra do not directly reflect the tertiary structure of the proteins, the Zn²⁺-binding also became comparable to the native protein.² This

suggests that the W464 mutants have the same overall structure as the NCoIE7 in their Im7 complexes.

Comparison of the disordered structures of W464A mutant and N-terminally truncated mutants – structural role of the N-terminal loop

The fact that Im7 binding recovered the Zn^{2+} binding capability of the point mutants – including changes at W464 site – suggested that their interaction with Im7 is strong.² It is well-known that Im7 inhibits the nuclease activity of NCoIE7 by interacting with the central helices of the latter protein.^{16,29} These regions of NCoIE7 otherwise provide strong DNA binding affinity.^{15,21,27} Together, these results suggest that the folding into the native-like tertiary structure promoted by the interaction with Im7 is not strongly dependent on the W464 residue but rather on the presence of the N-terminal chain. In this context, the structure of the W464 mutants became more unordered than that of the $\Delta N25$ -NCoIE7 mutant, which is surprising as the W464 residue belongs to the deleted 25 amino acid sequence. The latter residue is thus most probably responsible for the stabilization of fine structure of the active centre through interactions within the hydrophobic pocket. This also points out that it is difficult to predict the effect of mutations in terms of their effect on protein structure or function. Performing a virtual alanine scan – changing residues 450-470 to Ala one by one – and analysing these NCoIE7 mutants by semiempirical quantum chemical computations, the optimized structures did not differ significantly from the wild type protein.¹ Similarly, the SDM server for prediction of the effect of mutations – based on the calculated $\Delta\Delta G$ value of –0.90 kcal/mol for W464A NCoIE7 mutant – suggested only slight destabilization for W464A mutant without any functional effect,⁴³ in contrast to the solution structure of the purified protein and its decreased catalytic activity.¹ The more recent DUET server calculated $\Delta\Delta G$ of –2.53 kcal/mol for the above mutant.⁴⁴ Detailed computational analysis of the destabilization

effect of the mutations in the N-terminal sequence of NColE7 also assigned high contribution to W464 amino acid.¹

Consequences of structural activation on the possible application of NColE7 mutants in artificial nucleases

While the overall secondary structure composition of the mutant NColE7 proteins is restored by Im7, and similar changes occur in the presence of DNA,¹ the catalytic activity is drastically reduced or lost compared to the native enzyme. This suggests that the main function of the N-terminal sequence is not only to maintain the overall structure, but it directly participates in the catalytic process and in the stabilization of the fine structure of the functional active centre. Such a property provides the possibility of achieving allosteric control in designed artificial nucleases.^{45,46} Similar allosteric regulation has recently been suggested for e.g the c-Src kinase, based on the interdomain interactions restricting the conformational flexibility of the N-terminal intrinsically disordered region⁴⁷ or for the Pin1 peptidyl-prolyl isomerase.⁴⁸

Significance of the induced protein folding

Recently increasing attention is being favoured to the role of intrinsically disordered regions in proteins,^{49,50} including the investigation of disease related mutations or the development of potential drugs reordering a malfunctional mutated protein.⁵¹⁻⁵⁵ Accordingly, studies should extend towards the activation mechanisms through rather general structure recruitment in order to understand the functions of these proteins. Our findings on NColE7 mutants exemplify how intermolecular interactions trigger important structural stabilization of disordered proteins in solutions leading to functional entities. As disordered proteins are difficult to crystallize on their own, the standard procedure involves the cocrystallization with

substrates, inhibitors or other interacting partners.⁵⁶ The results easily draw focus on the induced order in structures, overlooking or underestimating the functional significance of originally disordered regions. Therefore, it is essential to supplement these data by spectroscopic techniques (e.g CD or NMR) sensitive to the solution structure of the individual interacting partners and to the structural changes upon their interactions,^{1,2,57} as well as to the dynamic nature of the protein structure.⁵⁸

A related example is the Im3 inhibitor, able to induce the native-like structure of a disordered Colicin E3 ribonuclease mutant⁴. The proof for this was primarily provided by CD and NMR spectroscopic methods,^{3,4} as the X-ray data were only available for the Im3 complexes of both the wild-type and the mutant enzymes^{4,59,60} with essentially the same structure, or with the substrate RNA.⁶¹

Induced folding is an essential way of protein regulation.⁶² Such phenomenon was earlier observed for the truncated staphylococcal nuclease. This mutant has a disordered structure, that is restored by the binding of 3',5'-bisphospho-2'-deoxythymidine inhibitor.⁶³

The ADPglucose pyrophosphorylase can also be reactivated after N-terminal truncation.⁶⁴

Furthermore, the structural disorder recognition was shown to be elementary feature of RNA and protein chaperone,⁶⁵ or antibody and disordered antigen interactions.⁶⁶ In the NF- κ B signaling module one of the subunits has a 30 amino acids long disordered C-terminal unit in the DNA-bound state, but adopts an ordered helical structure when binding to the I κ B α inhibitor.⁶⁷ The disordered part of the p53 tumor suppressor protein also initiated intense research, pointing to importance in phosphorylation and cancer related mutations.^{53,68-70}

The above results and statements draw attention to the importance in general of investigation of proteins in solution in the absence of their inhibitors, substrate analogue compounds or other binding partners, as intermolecular interactions often cause structural stabilization not present in the isolated protein.

Materials and methods

Construction of the genes and the expression and purification of the proteins

The pQE70 plasmid containing the gene of NCoIE7 and the Im7 immunity protein was a generous gift from Prof. K.-F. Chak, Institute of Biochemistry and Molecular Biology, National Yang Ming University, Taipei, Taiwan.⁵ The genes of the truncated mutants were amplified in PCR from this template as described earlier.²⁴ Because of the cytotoxicity of the NCoIE7 mutants containing the T454A and/or K458A and/or W464A changes, the genes of these proteins were cloned together with the DNA fragment encoding for Im7 protein.^{1,24} All the PCR fragments were inserted into a pGEX-6P-1 vector (GE Healthcare) providing an N-terminal glutathione-S-transferase (GST) affinity fusion tag. *E. coli* DH10B and *E. coli* BL21 (DE3) cells were transformed for DNA and protein production, respectively. The detailed conditions of the protein expression and purification procedures were described elsewhere.^{24,26} For the spectroscopic studies the GST fusion tag was cleaved off with Human rhinovirus C3 protease⁷¹ – sold as PreScission protease by GE Healthcare. The Im7 protein was separated from the mutant proteins by adjusting the pH to 3.0 and performing HPLC separation on a Sepharose SP FF 16/10 cation exchange column. The fractions of the nuclease mutants and Im7 were concentrated by Amicon ultrafilter with 5 kDa cutoff, and the buffer was exchanged to 20 mM HEPES, pH = 7.7. The sequences of the purified mutant proteins are shown in Figure 1 in comparison with the wild-type NCoIE7.

GST pull-down assay

GST-tagged truncated NCoIE7 variants, overexpressed together with the Im7 immunity protein within the bacterial cells, were obtained in PBS (pH = 7.3) buffer, and then

subjected to pull-down assay using Glutathione Sepharose 4B resin (GE Healthcare). The unbound proteins were washed away and the bound proteins were eluted from the resin by reduced glutathione solution of increasing concentration. The obtained fractions were analyzed by standard SDS gel electrophoresis using 12% polyacrylamide gel and Coomassie staining.⁷²

SRCD spectroscopic measurements

The Synchrotron Radiation Circular Dichroism (SRCD) spectra were recorded at the CD1 beamline of the storage ring ASTRID at the Institute for Storage Ring Facilities (ISA), University of Aarhus, Denmark.^{73,74} Camphor-sulfonic acid served as a calibration material for the instrument. All spectra were recorded with 1 nm steps and a dwell time of 2 s per step, using a 100.4 μm quartz cell (SUPRASIL, Hellma GmbH, Germany), in the wavelength range of 175-260 nm. The concentration of the protein solutions was adjusted to 3.2×10^{-5} M in 10 mM HEPES, pH = 7.7. The protein mixtures contained equimolar amounts of the nuclease mutants and the Im7 protein, each in 1.6×10^{-5} M concentration. From raw spectra the corresponding baselines (water or the appropriate buffer solution) were subtracted. The experimental CD intensities are reported in mdeg units. The CD signal was converted into differential molar absorbance units given with respect to the concentration of the backbone peptide groups for the analysis of secondary structure distribution by simultaneous application of a variety of programs published in the literature.³⁴⁻³⁹

Linear dichroism spectroscopy

Flow linear dichroism (FLD) spectra were measured on a Jasco-815 CD spectrometer equipped for linear dichroism spectroscopy, using a microvolume Couette flow device⁷⁵ with an annular gap of 0.25 mm giving a combined light path of 0.5 mm. An additional quartz lens

was mounted to allow for focusing onto the sample in the Couette cell, which was positioned as close to the photomultiplier as possible in the J-815 sample compartment. Water circulation through the metal block of the flow device thermostated the cell to 298 K. The sample volume was 70 μl and 3000 rpm rotation was applied. The optical bandwidth was 1 nm and the spectra were recorded in continuous mode between 190 and 400 nm with 50 nm/min scanning speed, 1 s integration time, 0.5 nm data pitch, and with 15 L/min nitrogen flow. Protein-DNA binding was studied with a 130 μM (final concentration calculated for base pairs) *calf thymus* DNA (CT-DNA) sample. The mixture contained 17 mM KH_2PO_4 , 2.4 mM HEPES (the pH of both buffers was adjusted to 7.7), 50 μM Zn^{2+} -ions and 0-5 μM protein. 60 μM EDTA was added to the NCoIE7 containing samples to assure that only the DNA binding effect of the enzyme is observed. The solutions were incubated for 10 min before recording the spectra.

The incubation time did not influence the results.

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Tables

Table I. The fractions of the secondary structure elements obtained from the crystal structures with programs DSSP³⁴ and BeStSel³⁵ or calculated from the SRCD spectra of the reference proteins^{36,37} by BeStSel,³⁵ the CDPro program package³⁸ and CDNN program.³⁹

Protein	Data	α -Helix	β -Sheet	Turn	Unordered
SRCD	CDPro	0.32	0.16	0.20	0.32
	CDNN	0.30	0.26	0.20	0.24
	BeStSel	0.20	0.21	0.16	0.43
SRCD (with Zn ²⁺)	CDPro	0.28	0.24	0.21	0.27
	CDNN	0.29	0.26	0.20	0.25
	BeStSel	0.16	0.24	0.16	0.44
NCoIE7 PDB id: 1M08 (with Zn ²⁺)	DSSP	0.38	0.17	0.15	0.31
	BeStSel	0.31	0.11	0.15	0.44
	PDB id: 1PT3 (with 8bp DNA)	0.39	0.17	0.12	0.32
SRCD (with Im7)*	CDPro	0.35	0.28	0.13	0.24
	CDNN	0.31	0.23	0.19	0.27
	BeStSel	0.19	0.25	0.16	0.40
PDB id: 7CEI (with Im7 and Zn ²⁺)		0.30	0.15	0.12	0.43
PDB id: 1MZ8 (with Im7 and Zn ²⁺)		0.36	0.17	0.20	0.27
PDB id: 2ERH (with Im7**)		0.32	0.17	0.15	0.36
SRCD	CDPro	0.43	0.12	0.19	0.26
	CDNN	0.44	0.15	0.18	0.23
	BeStSel	0.36	0.15	0.14	0.34
PDB id: 1CEI	DSSP	0.52	0.02	0.10	0.36
	BeStSel	0.48	0.00	0.11	0.41
Im7 SRCD (with NCoIE7)*	CDPro	0.53	0.2	0.14	0.13
	CDNN	0.46	0.13	0.17	0.23
	BeStSel	0.34	0.25	0.13	0.28
PDB id: 1MZ8 (with NCoIE7)		0.53	0.00	0.09	0.38
PDB id: 7CEI (with NCoIE7)		0.46	0.00	0.16	0.38
PDB id: 2ERH (with Im7**)		0.52	0.02	0.10	0.36

*The mathematical difference of the spectra of the mixtures and individual proteins were applied in the secondary structure determination. The result is distorted, as the fitted protein is supposed to suffer of all the conformational changes occurred in the protein complex.

**Proteins with redesigned interaction interface.

Table II. The fractions of the secondary structure elements calculated from the SRCD spectra of the N-terminally truncated proteins in the presence and absence of Im7. In comparison the data derived from *in silico* truncated crystal structures as the appropriate fractions of NCoIE7, are also given.

Protein	Data		α -Helix	β -Sheet	Turn	Unordered
	SRCD**	CDPro	0.23	0.20	0.20	0.37
		BeStSel	0.13	0.25	0.16	0.46
Δ N25- NCoIE7	SRCD (with Im7)*	CDPro	0.28	0.29	0.19	0.24
		CDNN	0.26	0.28	0.20	0.26
		BeStSel	0.11	0.32	0.17	0.40
	PDB id: 1M08 (with Zn ²⁺)		0.43	0.17	0.08	0.32
	PDB id: 7CEI (with Im7)		0.37	0.15	0.13	0.35
	SRCD**	CDPro	0.15	0.29	0.22	0.33
		BeStSel	0.12	0.27	0.17	0.43
Δ N45- NCoIE7	SRCD (with Im7)*,**	CDPro	0.20	0.20	0.20	0.31
		BeStSel	0.14	0.25	0.19	0.42
	PDB id: 1M08 (with Zn ²⁺)		0.45	0.15	0.07	0.33
	PDB id: 7CEI (with Im7)		0.37	0.15	0.14	0.34
Δ N69- NCoIE7	PDB id: 1M08 (with Zn ²⁺)		0.34	0.21	0.08	0.37

*The mathematical difference of the spectra of the mixtures and individual proteins were applied in the secondary structure determination (see the footnote of Table I).

**The evaluation of the spectra of low intensity by CDNN program³⁹ yielded unreliable data with a sum of fractions significantly higher than 1.00.

Table III. Effect of N-terminal mutations on the features of the NCoIE7 protein.

NCoIE7 variant	Im7 binding	DNA binding	Cytotoxicity	In vitro DNA cleaving activity	Solution structure
NCoIE7 ^{2,3,13,15,26}	+	+	+	+++	
W464A-mutants ^{2,3}	+	+	+	+	Partially disordered
T454A/K458A ³	+	+	+	+	NCoIE7-like
Δ N4-NCoIE7 ²⁵	+	+	-	-	NCoIE7-like
Δ N25-NCoIE7 ²⁵	+	+	-	-	Partially disordered
Δ N45-NCoIE7 ²⁴	+	-	-	-	Partially disordered
Δ N69-NCoIE7 ²⁴	-	-	-	-	Partially disordered

Figure legends

Figure 1. Scheme of the NCoIE7 variant sequences: the sequences of the purified NCoIE7 and Im7 proteins are also shown. The GPLGSPEF is an additional sequence encoded by the pGEX-6P-1 plasmid, which remained at the N-terminus of the nucleases after enzymatic cleavage of the GST purification tag. TKW symbolizes the TKW, TK, KW or W NCoIE7 point mutants, in which T454A and/or K458A and/or W464A mutations are present. For the truncated mutants X in the Δ NX notation indicates the number of deleted amino acids at their N-termini. The Im7 protein is purified together with a hexahistidine tag at its C-terminus.

Figure 2. Consequences of NCoIE7–Im7 interaction. (A) The comparison of the structures of free and bound Im7 and NCoIE7 proteins visualized from their single crystal structures. The free NCoIE7 structure (green, 1M08¹⁵), as well as the free Im7 structure (yellow, 1CEI²⁷) is superimposed to the structure of the NCoIE7-Im7 complex (blue, 7CEI²⁸). The Zn²⁺-ions are indicated by spheres. (B) The experimental SRCD spectra of NCoIE7 and Im7 proteins (3.2×10^{-5} M) and their equimolar mixtures (1.6×10^{-5} M, each). The mathematical sum of the component protein spectra considering the same composition as in the experiment, but assuming no interaction between the two proteins is also shown for comparison. (C) The same as (B) but the spectra were recorded in the presence of an equivalent amount of Zn²⁺-ions referred to the actual NCoIE7 concentration.

Figure 3. Im7 binding of truncated NCoIE7 mutants. The result of the GST pull-down assay showing the interaction of Im7 with N-terminally truncated NCoIE7 mutants in their GST-tagged forms. The first lane contains the Thermo Scientific™ Unstained Protein Molecular

Weight Marker. In lanes 3-5 the NColE7 proteins were shown to bind Im7 under the conditions of the GST-affinity purification, while the shortest mutant protein in lane 2 did not.

Figure 4. DNA binding of Δ N45-NColE7 mutant. Flow linear dichroism spectra of a 130 μ M (referred to base pairs) CT-DNA sample containing Zn^{2+} -ions (50 μ M) in the presence and absence of Δ N45-NColE7 (5 μ M). The spectra are compared with those of the same DNA sample incubated with increasing amounts of NColE7 (0.5-1.5 μ M) in the presence of 60 μ M EDTA to avoid DNA cleavage by the active enzyme.

Figure 5. Induction of the native-like structure of the TKW mutant in solution. Comparison of the experimental SRCD spectra of TKW mutant, NColE7 and Im7 proteins (3.2×10^{-5} M) and the equimolar mixtures of the nucleases and Im7 (1.6×10^{-5} M, each). The calculated spectral sum was constructed from the component spectra according to the initial composition of the measured system – thus, representing a spectrum of a mixture without interaction between the TKW mutant and Im7.

Figure 6. SRCD spectra of the N-terminally truncated NColE7 mutants. (A) Comparison of the molar SRCD spectra of the Δ N25, Δ N45-NColE7 truncated mutant proteins and that of the native NColE7. The calculation of the $\Delta\epsilon$ values was based on the average amino acid residue molecular weight for each protein. (B) Experimental spectra of Im7 protein and the Δ N45-NColE7 mutant (3.2×10^{-5} M, each) and their equimolar mixtures (1.6×10^{-5} M, each). The calculated spectra constructed from the component spectra are also shown for comparison. (C) Comparison of the experimental spectra of Im7 and the Δ N25-NColE7 mutant proteins (3.2×10^{-5} M, each) and their equimolar mixtures (1.6×10^{-5} M, each). The calculated spectra constructed from the component spectra are also shown.

Figure 7. The comparison of the induced folding in the Δ NX-NCole7-Im7 systems. Change in the distribution of secondary structure elements of Δ NX-NCole7 mutants as a consequence of the interaction with Im7 protein as calculated by the CDPro program package. The data on the NCole7 variants in complex with Im7 were obtained from the difference spectra of the complex and Im7 with the assumption that the structure of Im7 is stable and does not significantly change upon complex formation. (A) Δ N25-NCole7 mutant; (B) Δ N45-NCole7 mutant.

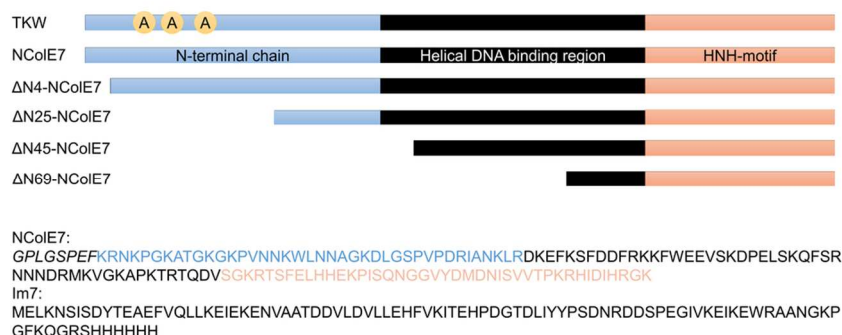


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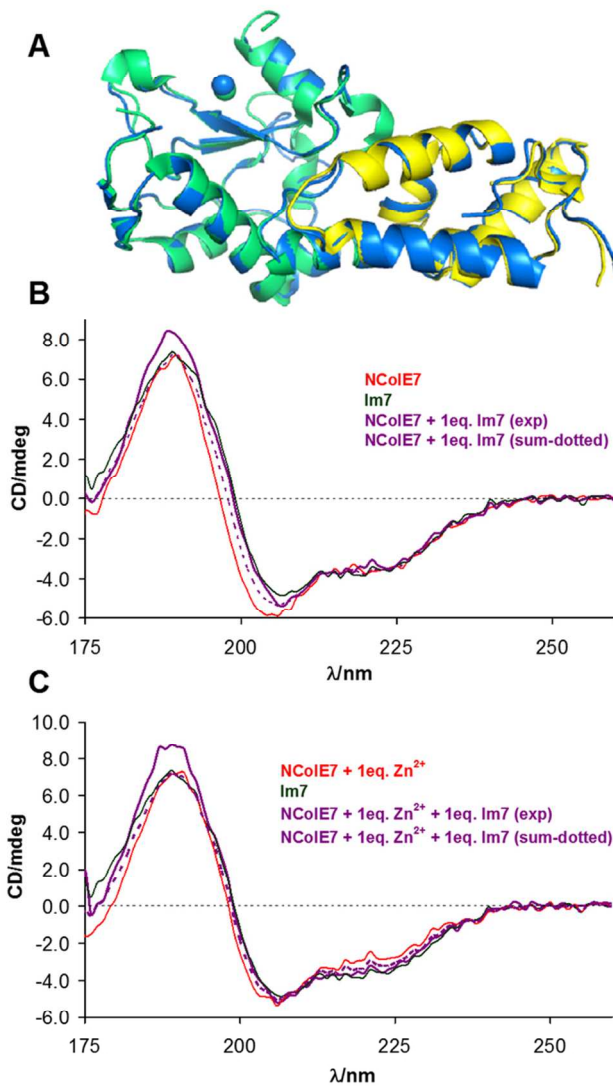


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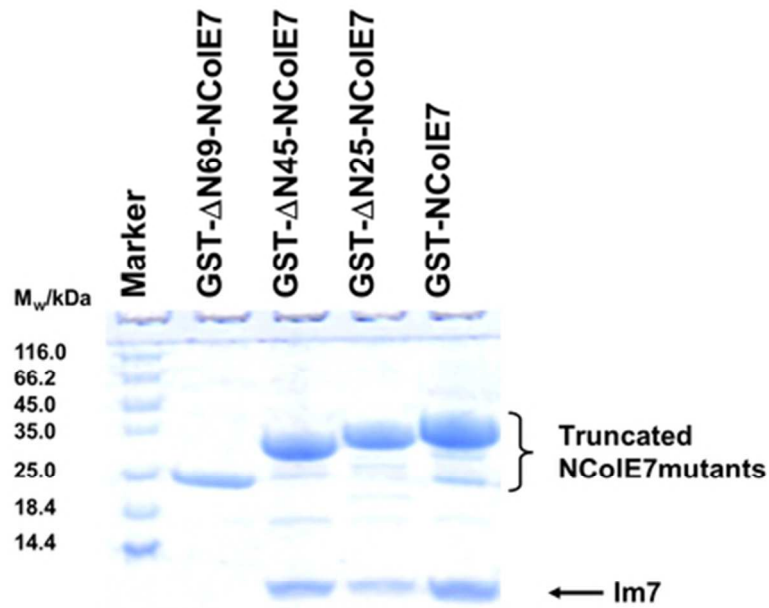


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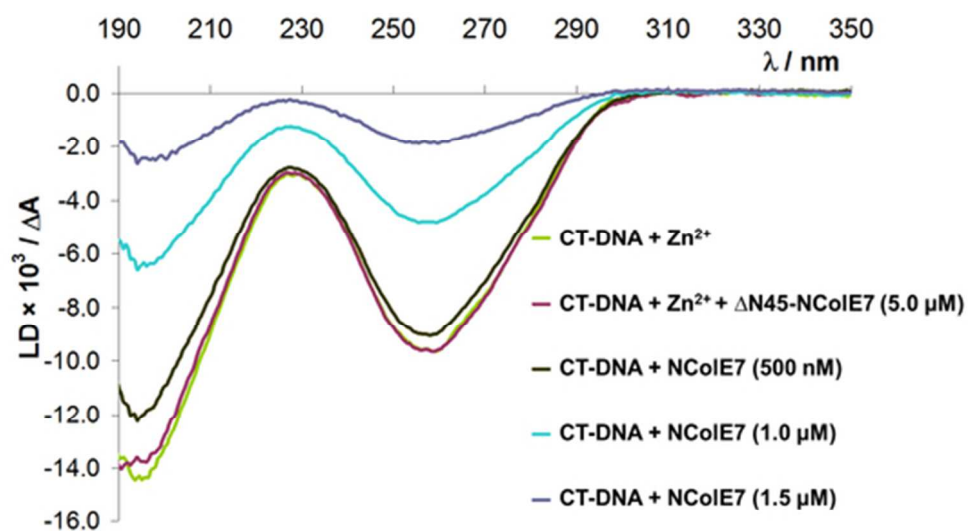


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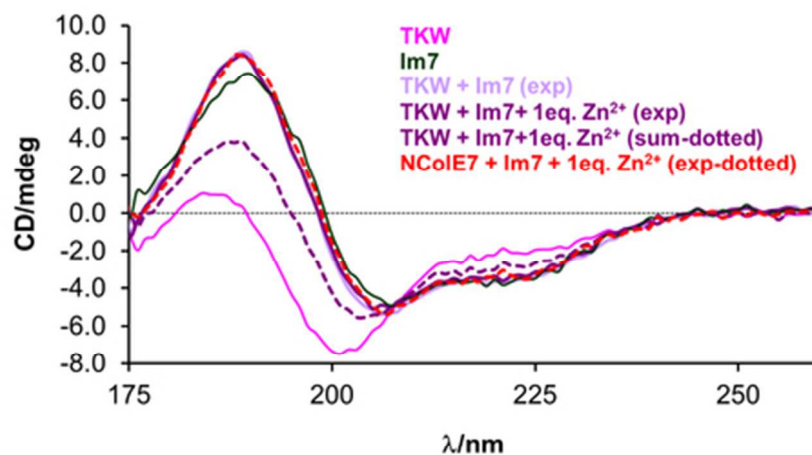


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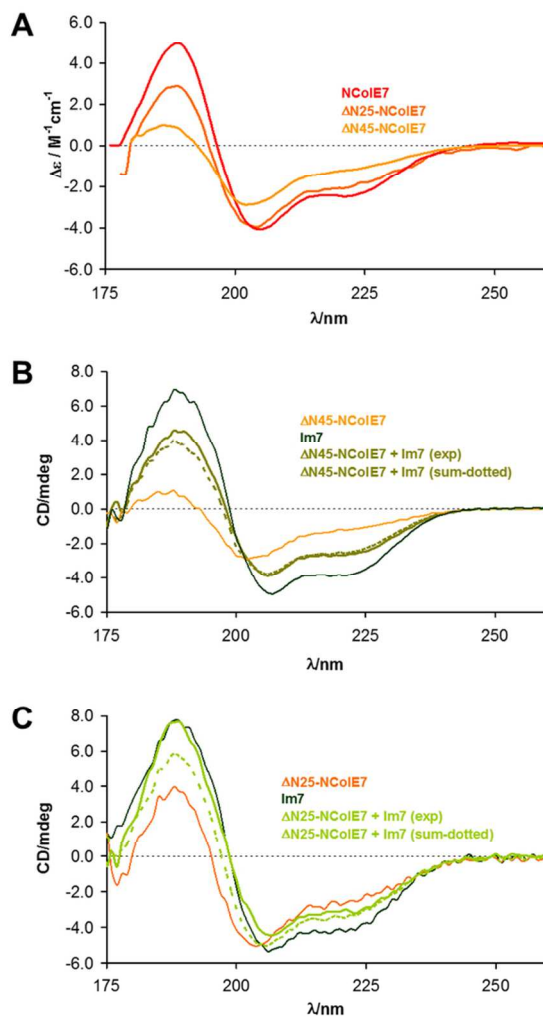


Figure 6. SRCD spectra of the N-terminally truncated NCoIE7 mutants. (A) Comparison of the molar SRCD spectra of the $\Delta\text{N}25$, $\Delta\text{N}45\text{-NCoIE7}$ truncated mutant proteins and that of the native NCoIE7. The calculation of the $\Delta\epsilon$ values was based on the average amino acid residue molecular weight for each protein. (B) Experimental spectra of Im7 protein and the $\Delta\text{N}45\text{-NCoIE7}$ mutant (3.2×10^{-5} M, each) and their equimolar mixtures (1.6×10^{-5} M, each). The calculated spectra constructed from the component spectra are also shown for comparison. (C) Comparison of the experimental spectra of Im7 and the $\Delta\text{N}25\text{-NCoIE7}$ mutant proteins (3.2×10^{-5} M, each) and their equimolar mixtures (1.6×10^{-5} M, each). The calculated spectra constructed from the component spectra are also shown.

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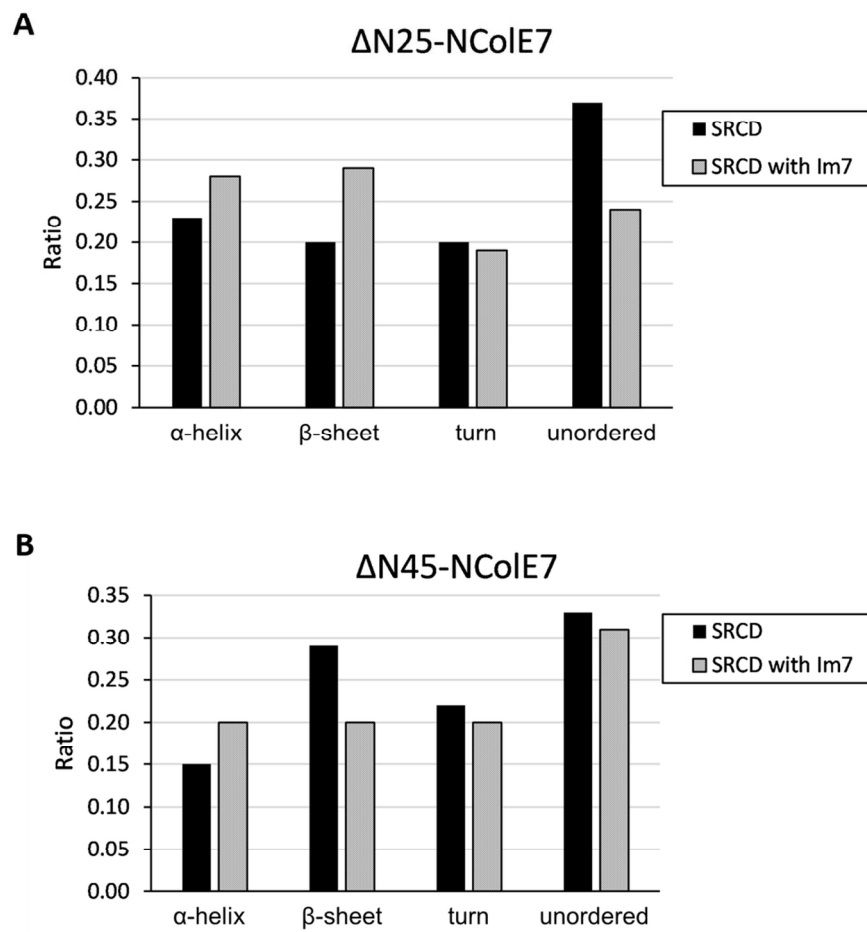


Figure 7. The comparison of the induced folding in the Δ NX-NColeE7-Im7 systems. Change in the distribution of secondary structure elements of Δ NX-NColeE7 mutants as a consequence of the interaction with Im7 protein as calculated by the CDPro program package. The data on the NColeE7 variants in complex with Im7 were obtained from the difference spectra of the complex and Im7 with the assumption that the structure of Im7 is stable and does not significantly change upon complex formation. (A) Δ N25-NColeE7 mutant; (B) Δ N45-NColeE7 mutant.

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