Solution Structure of the C-terminal Domain of TFIIH P44 Subunit Reveals a Novel Type of C4C4 Ring Domain Involved in Protein-Protein Interactions*

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The human general transcription factor TFIIH is involved in both transcription and DNA nucleotide excision repair. Among the 10 subunits of the complex, p44 subunit plays a crucial role in both mechanisms. Its N-terminal domain interacts with the XPD helicase, whereas its C-terminal domain is involved specifically in the promoter escape activity. By mutating an exposed and non-conserved cysteine residue into a serine, we produced a soluble mutant of p44-(321–395) suitable for solution structure determination. The domain adopts a C4C4 RING domain structure with sequential organization of β-strands that is related to canonical RING domains by a circular permutation of the β-sheet elements. Analysis of the molecular surface and mutation experiments suggests that the binding of p44-(321–395) to TFIIH p34 subunit is not mediated by electrostatic interactions and, thus, differs from previously reported interaction mechanisms involving RING domains.

TFIIH is a multiprotein complex that is required both in DNA repair through the nucleotide excision repair pathway and transcription (1, 2). Mutations in TFIIH subunits lead to severe genetic diseases such as xeroderma pigmentosum, Cockayne’s syndrome, and trichothiodystrophy (3, 4). TFIIH contains nine large subunits that form two structural and functional complexes; "core" TFIIH, comprising subunits p52, p34, p62, p44, and the XBP helicase, and the Cdk-activating kinase complex, comprising cdk7 kinase, MAT1, and cyclin H (Fig. 1A). The ninth subunit, XPD helicase, is associated with either the core TFIIH or the Cdk-activating kinase complex. Recently, an additional low molecular mass (8 kDa) subunit of TFIIH was identified, and its role in the DNA repair syndrome trichothiodystrophy group A was described (5). Several studies aiming at deciphering structure-activity relationships for components of the TFIIH complex have recently been reported. The structures of cyclin H (8) and domains of MAT1 (9) and p62 (10) have been solved at atomic resolution, and lower resolution electronic microscopy studies of the entire complex revealed a ring-like structure (6, 7).

Among the core TFIIH subunits, p44 plays a central role in the transcription/repair activities of TFIIH with distinct functions associated with each of its three domains (Fig. 1B); the N-terminal domain specifically regulates the DNA repair activity of the XPD helicase subunit (11), the central domain is essential for p62 subunit incorporation within TFIIH, and the C-terminal domain is mainly involved in promoter escape activity after the synthesis of the first phosphodiester bond by RNA polymerase II (12) but also interacts strongly with another core subunit, p34 (13). Mass spectrometry analysis showed that p44 binds three zinc ions, one by a C4 zinc finger motif in the central domain (residues 252–320) and two by the C-terminal domain (14). The sequence of the C-terminal domain of p44 reveals a high content of cysteine and histidine residues. The preliminary structural characterization of the C-terminal domain showed that the two zinc ions are bound using a cross-braced arrangement of coordinating residues in the sequence similar to RING domains. Identification of the eight coordinating residues by NMR was severely hindered by line broadening due to oxidative processes and intermediate time-scale dynamics as well as the high number of conserved putative zinc-coordinating residues. More especially, NMR data recorded on the wild-type p44-(321–395) domain were compatible with both a C6H2 and a C4C4 pattern of zinc coordinating residues, preventing a complete description of the domain structure (Fig. 1C). To determine unambiguously the zinc binding mode of the C-terminal domain of p44 and gain insight into its role within the TFIIH core particle, we expressed and purified the C381S mutant of this domain. The mutation of this non-conserved, solvent-exposed cysteine residue led to a dramatic improvement in the behavior of the domain, allowing us to define the zinc binding motif and to report a refined solution structure for this domain. Mutations of conserved hydrophobic residues on the surface of the domain provided further structural insights into the interaction with p34, unraveling a specific functional aspect of this new variant of RING domains.

MATERIALS AND METHODS

Sample Preparation—The C381S mutant of p44-(321–395) was cloned into a modified version of pGEX-4T2 (Amersham Biosciences) as previously described for other p44 mutants (14). Unlabeled and 15N-labeled recombinant proteins were expressed in Escherichia coli BL21(DE3) as glutathione S-transferase fusion protein using LB me-
dium and $^{15}$N-labeled rich medium (Silantes GmbH, Germany), respectively. Both media were supplemented with 6 $\mu$M ZnCl$_2$. Transformed bacteria were grown at 37 °C. Protein expression was induced at $A_{600}$ = 0.65 with 1 mM isopropyl-$\beta$-D-thiogalactopyranoside and harvested by centrifugation after 4 h at 30 °C. Cells were suspended in lysis buffer (50 mM Tris-HCl (pH 8), 200 mM NaCl, 10% glycerol, 0.1% Triton X-100, 5 mM $\beta$-mercaptoethanol, 0.1 mg/ml lysozyme, EDTA-free protease inhibitor mix), disrupted by sonication, and centrifuged at 100,000 $g$ for 1 h at 4 °C. The protein was purified from the cleared lysate using a GSH-Sepharose column (Amersham Biosciences), and the glutathione S-transferase was removed using bovine thrombin, leaving additional residues (glycine-serine-histidine) at the N terminus of the desired protein before the methionine. $p$44-(321–395) C381S mutant protein was finally purified using a Superdex 75 gel filtration column.

$^{1}$The abbreviations used are: HSQC, heteronuclear single quantum correlation; NOE, nuclear Overhauser effect; r.m.s.d., root mean square deviation; E2, ubiquitin-conjugating enzyme.
state of the imidazole rings of histidine residues was investigated using long range $^1$H,$^{15}$N HSQC spectra recorded on the zinc- and cadmium-loaded proteins with a magnetization transfer delay ($\frac{1}{2}J_{1H-15N}$) of 23 ms. The protonation state was deduced from the pattern of observed correlations as described (15). Vicinal scalar $J_{HN-HN}$ coupling constants were measured from the ratio of diagonal and cross-peak intensities in a three-dimensional HNHA experiment and converted into $\phi$-dihedral angle restraints (16).

Structure Calculation—The assignments of $^1$H and $^{15}$N chemical shifts and measurements of cross-peak intensities were achieved using XEASY (17). The NMR structure calculations were performed in CNS (18) using ARIA1.2 using default values for lower and upper distance restraints and for acceptance threshold (19). The automated assignment of the NOE cross-peaks was based on chemical shifts of $^1$H nuclei, allowing a frequency deviation of $\pm 0.015$ ppm in the acquisition dimension and $\pm 0.025$ ppm in the indirect dimension. Structure calculations were started from a random initial structure that included the two zinc atoms assuming a tetrahedral geometry of the zinc coordination (Zn-S$_\gamma$ bond lengths were set to 2.3 Å, and C$_{\beta}$-S$_\gamma$-Zn and S$_\gamma$-Zn-S$_\gamma$ angles were set to 109.5$^\circ$). Of the 50 structures computed in the final iteration, the 10 lowest energy structures were refined in a shell of water molecules using a torsion angle data base potential (20) using XPLOR-NIH (21). The final ensemble of conformations was analyzed by PROCHECK (22) and visualized with MOLMOL (23). Structural alignments were obtained using WHATIF (24).

RESULTS AND DISCUSSION

The Fold of the C381S Mutant of p44-(321–395) Domain Is Identical to That of the Wild-type Domain—The ability of the 75 C-terminal residues of the human TFIIH p44 subunit to bind two zinc atoms and fold autonomously into a RING domain-like structure was reported previously (14). However, extensive line broadening observed for several residues prohibited the precise definition of the second zinc binding motif despite extensive mutagenesis of putative zinc coordinating residues. Assuming this behavior of the p44-(321–395) domain to result from possible oxidative processes involving exposed cysteines, we mutated cysteine 381, which is not conserved among species, into a serine residue. The mutation led to a striking improvement in behavior of the recombinant protein. The sample lifetime was dramatically lengthened as shown by the reproducibility of NMR experiments over time. Moreover, values of translational diffusion coefficients measured using pulsed field gradient experiments were compatible with diffusion as a monomer (data not shown), suggesting that, in contrast to the wild-type protein, the C381S mutant of p44-(321–395) is not prone to oxidation.

FIG. 2. $^1$H,$^{15}$N HSQC spectra of p44-(321–395) domain at 303 K. A, superposition of spectra of $^{15}$N-labeled wild-type (black) and mutant (red) proteins. Side-chain amide resonances are identified by labels in italics. B, cross-section along the F2 dimension through selected amide proton resonances in the $^{15}$N-coupled $^1$H,$^{15}$N HSQC spectrum.

FIG. 3. Zinc-cadmium replacement experiment. A, chemical shift differences of the amide $^1$H (black bars) and $^{15}$N (gray bars) nuclei between the zinc- and cadmium-loaded proteins. The values of $\Delta\delta$ were calculated as follows: $\Delta\delta = \delta$(Zn$^{2+}$ form) $- \delta$(Cd$^{2+}$ form). B, $^1$H,$^{113}$Cd HSQC spectrum of the cadmium-loaded sample.
Chemical modification of wild-type p44-(321–395) showed that Cys-381 is the only solvent-accessible cysteine (data not shown). The three-dimensional structure of the C381S mutant of p44-(321–395) was, therefore, expected to be very similar to that of the wild-type protein. Indeed, the pattern of cross-peaks in a $^{1}H,^{15}N$ HSQC spectrum of the mutant closely matches that of the wild-type protein, indicating that the mutation does not alter the fold of the domain (Fig. 2A). Sequence-specific assignments of the C381S mutant of p44-(321–395) were obtained from both homonuclear and $^{15}N$-edited spectra. $^{1}H,^{15}N$ correlations for 8 residues in the N-terminal region (including the four additional residues, GHSM, resulting from cleavage of the glutathione S-transferase fusion protein) were not observed, and the resonances for those residues were, therefore, left unassigned. An analysis of chemical shift differences between wild-type and mutant p44-(321–395) along the protein backbone confirms that the mutation does not lead to any major modification of the protein structure; chemical shift differences for non-exchangeable protons never exceed 0.1 ppm, even for residue 381. The mutation mainly affects the chemical shifts of a small continuous stretch of residues C-terminal to the mutation site (Cys-382 to His-387). A few residues in the N-terminal part of the domain (Ser-321 to Phe-331) also undergo chemical shift modification upon mutation despite their remote location in the sequence. These changes may indicate that the N-terminal region, whose conformation could not be determined for both the wild-type and mutant proteins, interacts with residues in the vicinity of the second zinc-binding site.

The C381S mutation results in a global and a site-specific reduction in line width for several resonances in the $^{1}H,^{15}N$ HSQC spectrum.
The HSQC spectrum, indicating a decrease of both the overall correlation time and the exchange contributions of the ms time scale motions. This effect is particularly striking for 2 residues preceding the mutation (Val-375 and Leu-379) (Fig. 2A). The overall reduction in line widths allowed the observation of the homonuclear proton coupling multiplet patterns for most of the peaks in a 1H,15N HSQC spectrum recorded without 15N decoupling. The relative intensities of inner and outer components of the multiplet are modulated by cross-correlated relaxation of HN-N and HN-H dipolar interactions and, therefore, provide an efficient way to determine the sign of angles in medium-sized proteins (25). The pattern observed for both Gln-364 and Gln-349 indicates positive values of angle for these residues (Fig. 2B).

The Two Zinc Ions of p44-(321–395) Are Coordinated by Eight Cysteine Residues—Unambiguous assignment of the zinc binding residues of the C381S mutant of the human p44-(321–395) sequence. The structural alignment of p44-(321–395) sequences with those of other RING domains requires the N-terminal of p44-(321–395) to be cut and pasted at the end of the p44 RING domain at a position indicated by a pair of scissors. The secondary structure of p44 and MAT1 RING domains is indicated above the alignment using a color scheme that follows the order in the primary sequence (from yellow for 1 to red for 3). Shown are ribbon diagrams of the C4C4 RING domain, p44-(321–395) (B) and of the C3HC4 RING domain, MAT1-(1–65) (C). For the sake of clarity, only residues 328–387 have been represented for p44. Helices are shown in blue, and the -sheets are colored as described above. The side chains of conserved hydrophobic residues are shown in green.

**Fig. 5. Comparison of p44-(321–395) with RING domains.** A, alignment of p44-(321–395) sequences and structural alignment of RING domains from the FSSP data base. Filled circles indicate structurally equivalent positions (r.m.s.d. less than 2.5 Å) between the RING domains of p44-(321–395) and RAG1 (PDB code 1g25) and between p44-(321–395) and the C4C4 RING domain of CNOT4 (PDB code 1e4u). The metal-coordinating residues are shown in magenta. Conserved hydrophobic residues are shown in green, and conserved positive residues are shown in orange. Boxed positions indicate residues that have positive angle in the C381S mutant of the human p44-(321–395) sequence. The structural alignment of p44-(321–395) sequences with those of other RING domains requires the N-terminal of p44-(321–395) to be cut and pasted at the end of the p44 RING domain at a position indicated by a pair of scissors. The secondary structure of p44 and MAT1 RING domains is indicated above the alignment using a color scheme that follows the order in the primary sequence (from yellow for 1 to red for 3). Shown are ribbon diagrams of the C4C4 RING domain, p44-(321–395) (B) and of the C3HC4 RING domain, MAT1-(1–65) (C). For the sake of clarity, only residues 328–387 have been represented for p44. Helices are shown in blue, and the -sheets are colored as described above. The side chains of conserved hydrophobic residues are shown in green.
Solution Structure of the C381S Mutant of p44-(321–395)—
The sharp reduction in line broadening due to exchange contributions allowed the solution structure of p44-(321–395) to be refined. The dataset for structure calculations consisted of 1294 unambiguous intra- and interresidue distance restraints derived from two-dimensional NOE spectroscopy spectra, 17 hydrogen bond distance restraints, and 32 backbone dihedral restraints including positive \( \phi \) angles determined from \(^1\)H-coupled \(^1\)H,\(^{15}\)N HSQC spectra (Fig. 4A and Table I). For the final ensemble of the 10 lowest energy structures resulting from ARIA calculations, the root mean square deviation for the \( \phi \) positions of residues 328–386 is 0.98 Å, indicating a significant improvement in the quality of the structures (Fig. 4B, Table I). A significant increase in the number of long range NOEs in the C-terminal part of the domain (residues 380–387) (Fig. 4A) allowed the definition of a region whose conformation could not previously be determined due to extensive line broadening in the wild-type protein. This is reflected in lower r.m.s.d. values for the C-terminal part of the domain, encompassing the last pair of cysteine residues involved in the second zinc-binding site (Cys-382, Cys-385) (Fig. 4C). The central region of p44-(321–395) spanning residues 328 and 388 is well structured, whereas the structure of the N- and C-terminal regions is less precisely defined due to a lack of experimental restraints. \(^{15}\)N heteronuclear relaxation measurements show that the corresponding amide groups are affected by motions on multiple time scales, preventing the definition of a single conformation for these regions (data not shown). The improvement in the quality of the structure is readily apparent from the Ramachandran plot statistics. Positive \( \phi \) angles were experimentally defined from cross-correlated relaxation rates for Gln-349 and Gln-364, accounting for more than half of the residues in the disallowed regions. Other residues whose dihedral angles lie in less favored regions are located mostly in poorly defined regions of the structure and display high values of the \( \phi \) angle order parameter (Fig. 4B).

The solution structure of the C381S mutant of p44-(321–395) is similar to that of the wild-type (Fig. 4C), with an r.m.s.d. of 1.9 Å resulting from the best-fit superimposition of 33 \( \alpha \) atoms on the well defined parts of the average structures. The structure consists of a triple-stranded anti-parallel \( \beta \)-sheet comprising residues Phe-331—Ile-334 (\( \beta \)1), Gln-355—Val-359 (\( \beta \)2), and Val-366—Cys-368 (\( \beta \)3) followed by a short C-terminal \( \alpha \)-helix that is tightly packed onto the \( \beta \)-sheet. Both zinc ions are involved in stabilizing loops, one connecting the first and the second strand of the \( \beta \)-sheet (loop1, Pro-335 to Asp-339) and the other running from the end of the \( \alpha \)-helix to the C terminus (loop2, His-376 to Lys-388). The distance between the two zinc ions is 14.8 ± 0.5 Å. The conformation of the N-terminal part of loop1 between Pro-335 and the first zinc binding residue Cys-345 is poorly defined due to high flexibility.

Structural Relationship with Other RING/UBD Domains—
The fold of p44-(321–395) is stabilized by a cluster of conserved hydrophobic residues including Phe-331, Leu-352, Tyr-358, Phe-367, and Val-375, and a similarity with the C3HC4 RING domains was noted previously (14). The structural alignment of p44-(321–395) sequences with a similar analysis of C3HC4 RING and U-box domains from the FSSP data base (29) shows that these hydrophobic residues are conserved across the whole family of RING folds (Fig. 5A). Interestingly, four of these residues are also conserved in the U-box domains. U-box domains have a similar structure to that of RING domains, but they lack the two zinc ions whose contribution to the stability of the fold is replaced by an extensive set of hydrogen bonds (30, 31). It is worth noting that the structural superposition of p44-(321–395) on a triple-stranded C3HC4 RING domain such

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ring domains (33). Zinc-coordinating residues. It appears to be a characteristic of the second process (26). The two domains share a characteristic spacing of four residues for the interaction (39). A comparison of p44 sequences of UbcH5B has been described in detail (37, 38). Site-directed mutagenesis for binding. In the C4C4 RING domain as of RING domains and also for the U-box domain (35, 36). For function has been experimentally demonstrated for a number conjugating enzyme (E2)-dependent ubiquitination (34). This involved in regulating protein levels by mediating ubiquitin-structure. Site-directed mutagenesis established the importance of negatively charged residues for the interaction (39). A comparison of p44 sequences with those of other RING domains reveals specific features of the p44 C4C4 RING (Fig. 5A). Its α-helix contains two conserved aspartic acid residues and higher number of hydrophobic residues than other RING domains. It should be noted that the position of Asp-372, which follows the third pair of zinc binding residues, is occupied by a hydrophobic residue in all other RING structures. These sequence features may reflect a distinct biological function of the C4C4 RING domain of p44. No interaction with enzymes from the ubiquitination pathway has yet been reported so far for TFIIH subunits including p44. However, p44 interacts strongly with several other subunits of the TFIIH complex, including p62 and the two helicases XPB and XPD as well as p34 (40, 41). For this latter interaction, it was further shown that co-expression of p44-(321–395) with the N-terminal 242 residues of p34 produces soluble complexes, possibly the role of certain residues in the interaction with p34, point mutations were introduced into p44-(321–395), mapping the first zinc-binding site and the α-helix. The mutation of hydrophobic residues in the vicinity of the first zinc-binding site does not affect binding to p34, but the mutation of a single cysteine residue forming this site leads to the loss of a soluble complex, showing that the conservation of the fold is required for binding. In the α-helix, the mutation of the conserved acidic residues Asp-370 and Asp-372 into arginine does not prevent binding to co-expressed p34-(1–242), suggesting that the formation of the complex is not governed by electrostatic interactions involving these residues (Fig. 6). A striking feature of the p44-(321–395) α-helix is the presence of Phe-374, which is exposed to the solvent. In RING domains, which are involved in the ubiquitination pathway, this residue is replaced by a polar residue, which is important for binding to the E2-conjugating enzyme (37, 34). Mutation of Phe-374 into serine results in no stable complex being formed. Although the lower expression rate of soluble p44-(321–395) for this mutant does not allow unambiguous conclusions to be drawn, it appears that binding to p34 is not mediated by electrostatic interactions but more likely by hydrophobic contacts, thus differing from the interaction mechanism that was described for the C4C4 RING domain of CNOT4.

In conclusion, the solution structure of p44-(321–395) shows that its topology differs from that of other reported RING domains by a circular permutation of the extended secondary structure elements. Site-directed mutagenesis suggests that the tight binding to p34 is mediated by hydrophobic interactions and involves residues on the solvent-exposed face of the α-helix. The structure of p44-(321–395) sheds new light on the versatile nature of protein-protein interactions mediated by RING domains.

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