Rational Design of p53, an Intrinsically Unstructured Protein, for the Fabrication of Novel Molecular Sensors*

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The dominant paradigm of protein engineering is structure-based site-directed mutagenesis. This rational approach is generally more effective for the engineering of local properties, such as substrate specificity, than global ones such as allostery. Previous workers have modified normally unregulated reporter enzymes, including β-galactosidase, alkaline phosphatase, and β-lactamase, so that the engineered versions are activated (up to 4-fold) by monoclonal antibodies. A reporter that could easily be “reprogrammed” for the facile detection of novel effectors (binding or modifying activities) would be useful in high throughput screens for directed evolution or drug discovery. Here we describe a straightforward and general solution to this potentially difficult design problem. The transcription factor p53 is normally regulated by a variety of post-translational modifications. The insertion of peptides into intrinsically unstructured domains of p53 generated variants that were activated up to 100-fold by novel effectors (proteases or antibodies). An engineered p53 was incorporated into an existing high throughput screen for the detection of human immunodeficiency virus protease, an arbitrarily chosen novel effector. These results suggest that the molecular recognition properties of intrinsically unstructured proteins are relatively easy to engineer and that the absence of crystal structures should not deter the rational engineering of this class of proteins.

Cells generally employ sensor proteins (also called “biosensors” or “switches”) to detect chemical stimuli and activate downstream components of signal transduction systems. We sought to fabricate artificial molecular sensors by engineering proteins that are specifically activated when bound or modified by novel effectors. Such sensors have practical utility in high throughput screens for drug discovery or directed protein evolution. They have also proved to be useful as research reagents. For example, two-hybrid systems (1, 2) and protein fragment complementation assays (3) couple the interactions of fusion proteins within transgenic cells to the production of signals. Cleverly designed sensors based upon fluorescent resonance energy transfer between green fluorescent protein analogues have also enabled the observation of intracellular protein modification events (4), including protein phosphorylation (5) and proteolysis (6). We expect that the utility of engineered protein sensors will continue to increase as they are deployed as diagnostic reagents (7) and pathogen-activated biotherapeutics (8, 9).

Rational protein design is generally synonymous with structure-based site-directed mutagenesis (10). Reporter proteins are usually selected as starting points for sensor design because their structure have been solved and because their activities are amenable to high throughput screening. Previous workers have inserted peptide epitopes into β-galactosidase (11), alkaline phosphatase (12), or β-lactamase (13). This approach has generally produced catalytically compromised enzymes that are activated up to 4-fold by antibody binding (14), presumably through allosteric mechanisms (7). It nevertheless remains difficult to predict whether the insertion of any peptide epitope into a particular position of a protein will generate the desired antibody-dependent activity. In contrast, natural selection has no bias in favor of proteins that crystallize readily or those with spectroscopically detectable activities. It has in effect generated vast numbers of proteins that are regulated through modification or binding, presumably through parsimonious evolutionary pathways. We therefore considered nature’s solutions to the problem of sensor design before formulating our own strategies.

By choosing globular and normally unregulated reporter enzymes such as β-galactosidase and alkaline phosphatase, protein engineers may be undertaking unnecessarily difficult design problems. In contrast, natural proteins that participate in signal transduction and gene expression tend to be intrinsically unstructured (15). The unbound forms of these proteins have been described as “beads on a flexible string,” where the beads are domains (often molecular recognition elements) connected by linkers (16). We hypothesized that intrinsically unstructured proteins are easy to engineer because of their inherent modularity and relative absence of functional constraint.

Our strategy was therefore to fabricate novel sensors by engineering an intrinsically unstructured protein. Sensors that are activated are preferable to those that are inactivated because the latter are more likely to produce “false positives” during high throughput screens. Lim and coworkers (17) previously reprogrammed the effector dependence and gating behavior of the neuronal Wiskott-Aldrich syndrome protein (N-WASP), which also contains unstructured regions (according to the DisProt data base, Ref. 18). N-WASP is modular in design and easily reprogrammed, but its activity (actin polymerization) is not particularly convenient to assay.

We chose the transcription factor p53 as a starting point for several reasons. It is an important tumor suppressor, so its structure and function are well understood (Fig. 1). Regions within the N and C termini of p53 are thought to be intrinsically unstructured (19, 20) and are therefore likely to accommodate almost any insertion. The wild-type p53 remains inactive in vitro until the C-terminal 30 amino acids are bound by an antibody, deleted, or phosphorylated (21). The exact mechanism of activation remains unclear (22) but can nevertheless be exploited. The sequence-specific DNA binding activity of p53 can be detected in...
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p53 binds double-stranded DNA with two adjacent copies of the consensus sequence 5'-PuPuPuCA/T(T/AT)GPyPyPyP-3' (23), and its transcription activation activity in cultured cells is dependent on DNA binding (24). We and others employ the artificial p53CON target sequence, 5'-GGACATGGCGGGATCTGC-3', which was isolated from a pool of random sequence double-stranded oligonucleotides (25).

Active p53 protein can be expressed in Escherichia coli and is thus inexpensive and easy to produce. The high affinity of p53 for p53CON (KD = 5 × 10^-10 M, (26)) enables highly sensitive assays. Active and latent p53 proteins differ greatly in sequence-specific DNA binding activity. In fact, the "activation factor" we observed of p53 (as high as ~100-fold increase in signal) greatly exceeds those of textbook allosteric enzymes (<70% increase, (27)). The signal produced by p53 in vitro remains constant once it reaches equilibrium, so assays are less time dependent and labor intensive than those that employ enzymes.

Here we have demonstrated the versatility of p53-based molecular sensors. Site-directed insertion mutagenesis and heterologous expression were used to fabricate p53 variants that display peptides recognized by p53 antibodies (human immunodeficiency virus (HIV), Bacillus anthracis Lethal Factor) or monoclonal antibodies (three different epitopes). All of the p53 variants were specifically activated by their cognate epitopes. These sensors have immediate utility in high throughput screens and could potentially be used in other applications (see "Discussion"). More importantly, this work has demonstrated a simple but effective alternative to structure-directed site-directed mutagenesis for the fabrication of artificial sensors.

EXPERIMENTAL PROCEDURES

Materials—Expression vectors pET20b+, pET28a+, and pCDF Duet were from Novagen (Madison, WI). The p1+IQ HIV protease expression vector (ATCC number 68352) and the human p53 cDNA (ATCC number 57254) were obtained from the American Type Culture Collection. The Lethal Factor expression vector, pLF, was a gift from Dr. Stephen Leppla. E. coli strain BL21(DE3) Gold/pLysS was from Stratagene (La Jolla, CA); E. coli strain InvEc was from Invitrogen. γ-labeled P-32 ATP was from MP Biomedicals (Irving, CA) and Butterfly nitrocellulose membranes from Schleicher and Schuell. Oligonucleotides were synthesized by IDT (Coralville, IA); the IRD-700-labeled oligo was from Applied Biosystems (Foster City, CA).

Construction of Protease Expression Vectors—The inducible HIV protease expression vector, p1+IQ (lacZ) was constructed as follows. The lacZ gene was excised from expression vector p1+IQ (30) using BamHI; the remaining DNA was purified, self-ligated, and used to transform E. coli strain InvEcA. The Pbad+HF-PR-pCDF expression vectors were constructed in two stages. First, we made the Pbad+PCDF expression vector by subcloning the araC repressor and Pbad+ promoter from pBAD myc His A into pSI1180 using SpHl and NcoI; the Pbad+ promoter was then subcloned from PBad+PSI1180 into pCDF Duet using Ncol and XbaI. Second, the HIV protease gene in p1+IQ was PCR amplified, subcloned into pET28+ using NdeI and Hind III, and sequenced to confirm its wild-type identity. The subcloning fused DNA encoding a hexahistidine tag to its 5'-end; this tag does not affect enzyme activity (31). The inactivating D25N mutation was introduced into His5-HIV PR-pET28 by whole circle PCR using primers 5'-GATCCTCTATTAAATACAGGAGCAGATG-3' (HIVPR-D25N-62) and 5'-CTTTGACATCCCTCCATTTAATG-3' (HIVPR-D26out). The wild-type and D25N variants of the His5-HIV PR gene were subcloned from their respective His5-HIV PR-pET28 plasmids into PBad+PCDF using Ncol and Xhol.

The Lethal Factor protease gene was cloned from the pLF vector. The signal peptide and an internal Ncol site was removed using two-step cloning (based on Park and Leppla, Ref. 32). The first PCR reaction used the primers 5'-AAAAACCATGGGGGGGTACTGCT-3' (5'-LF NcoI) and 5'-TTGAAGTTCCATCGAATATAGAAAGCG-3' (LF 2088re). The second PCR reaction used primers 5'-CGTCTCTTATTTATCTGAGTCTCAAAA-3' (LF 2126) and 5'-TTTTGCTGGGCCGATCTTATGGAATAATAA-3' (3'L BamHI). The two products were combined in a third PCR reaction in which the entire Lethal Factor gene amplified using the external 5'-LF Ncol and 3'-LF BamHI primers. The Lethal Factor gene was then cloned into the pCDF Duet vector (Novagen) for the in vivo expression of the Lethal Factor protease.
assays. All variants were sequenced using the Applied Biosystems Big Dye protocol at the Center for Fundamental and Applied Molecular Evolution (Emory University).

**Protein Purification—** *E. coli* BL21 (DE3) cells containing the plasmid pLysS were transformed with constructs that expressed the wild-type or engineered p53 genes fused to N-terminal six-histidine tags. The transformants were grown at 37 °C to mid-log (A600 = 0.3) and then induced with 0.5 mM isopropyl-thio-galactopyranoside (IPTG) and shaken at 23 °C for 4 h. The cells were spun down and stored as a pellet at −80 °C. The cells were lysed by sonication and the insoluble fraction removed by centrifugation. The protein was purified as described in the pET manual (Novagen) except that the binding, wash, and elution buffers were replaced with p53 binding buffer (10 mM Tris-HCl, pH 7.6, 50 mM NaCl, 10% glycerol, 0.1% Triton X-100, and 5 mM β-mercaptoethanol) without β-mercaptoethanol, plus 450 mM NaCl and 0, 60, and 1000 mM imidazole, respectively. The eluted p53 proteins were dialyzed in p53 binding buffer (plus 450 mM NaCl) and stored in p53 binding buffer (plus 45% glycerol and 450 mM NaCl) at −20 °C. The total protein concentration was quantified using the Bradford protein assay (Bio-Rad). HIV protease was purified and refolded according to an established protocol (31) and protein concentration also quantified using the Bradford protein assay. We used a commercially available fluorescent substrate to show that our HIV protease was as active as those described in the literature (33).

The p53/p6 expression vector was co-expressed with HIV protease by induction with 0.5 mM IPTG for 4 h at 23 °C, whereas the p53/LF10 expression vector was co-expressed with Lethal Factor by induction with 0.5 mM IPTG for 18 h at 18 °C. The wild-type and engineered p53 proteins were expressed, either alone or co-expressed with HIV protease (from p1 +IQ (30)) or LF protease (from LF-pCDF), and purified by immobilized metal affinity chromatography (IMAC) as described above. The purified p53 proteins (2 μM) were incubated with 1.0 μM N-terminal infrared-labeled oligo p53CON, 50 ng of pLS1180, and 10 μg of bovine serum albumin in a final volume of 20 μl. After a 30-min incubation on ice, the mixtures were loaded onto 4% acrylamide gels and evaluated by electrophoretic mobility shift assay (EMSA) as described below.

**EMSA Assays—** The EMSAs were performed as described (34) except p53 binding buffer was used. The purified proteins (50 nM p53-Δ30, 10 nM p53-Δ68, 10 nM p53-HA-Δ68, 10 nM p53-LF(ab)-Δ68, 20 nM p53-HSV-Δ68) were incubated with 1.0 μM 5′-IRD700-labeled oligo p53CON (5′-ATGGGATGCGCCGGGCAAGTTCC-3′ (25)) and 0.25–1.0 μg of monoclonal antibodies in a total volume of 20 μl. After a 30-min incubation on ice, the mixtures were loaded onto 4% acrylamide gels (19:1 acrylamide to bisacrylamide, 0.33 TBE, 0.1% Triton X-100) and run at 200 V for 1 h at 4 °C. The gels were scanned using the LiCor Odyssey Infrared Imager; the intensities of the pixels within each band were quantified with the associated Odyssey software (version 1.1). The activation factors were calculated by dividing the intensities of the antibody/engineered p53/p53CON complexes by the intensity of the engineered p53/p53CON complex.

The in vitro protease assays were performed using purified p53 (p53/p6, p53/LF10, p53Δ30, or wild-type) and protease (HIV protease (31) or Lethal Factor) proteins. The purified p53 proteins (2 μM) were reacted with the HIV protease (10 μM) or LF (2 μM) proteases (EMD Biosciences) for 48 h in p53 binding buffer at 4 °C. Following the incubation, the p53 activity was determined by EMSA as described above.

**High Throughput Assay—** The screen for p53 function is based on a method developed by Singh et al. (35). *E. coli* strain BL21 (DE3) cells carrying the T7 lysozyme expression vector, pLysS, were transformed with the p53 expression constructs and plated on Luria Broth (LB) plates containing 34 μg/ml chloramphenicol and 100 μg/ml kanamycin (LB-kan/chl). After 16 h of growth at 37 °C, the colonies were adsorbed onto a nitrocellulose filter and transferred colony-side-up to LB-kan/chl plates containing 0.5 mM IPTG to induce expression of p53. The colonies adsorbed to the nitrocellulose filter were induced at 23 °C for 4 h. The cells remaining on the original plate were regrown into full colonies by a further 8 h of incubation at 37 °C.

The cell membranes of the p53-expressing colonies were disrupted with chloroform gas for 15 min, giving the intracellular T7 lysozyme access to the peptidoglycan. The remaining manipulations were carried out in p53 binding buffer (described above) at 23 °C. The filters were treated with 2.5 units/ml DNase I (in p53 binding buffer plus 10 mM MgCl₂) for 15 min, blocked with 5% nonfat dry milk (in p53 binding buffer plus 40 mM Tris-HCl, pH 7.6) for an hour, washed three times in binding buffer for 5 min each, and probed with 20 nM radiolabeled oligonucleotide containing the p53CON sequence (underlined) 5′-GTGGACATGCCCAGGCAATGCTCC (25) (plus 5 μg/ml denatured salmon sperm DNA) for 1 h. The fluorescent IRD700-p53CON probe apparently interacts non-specifically with endogenous *E. coli* proteins (data not shown) and is therefore unsuitable for the colony lift screen. The filters were washed four times more for 7.5 min each, and the quantity of probe bound to each filter was measured using a BAS-1000 Bio-imaging Analyzer System (Fujiﬁlm Medical Systems USA, Stamford, CT).

**RESULTS**

**Protease Activation of p53**

*In Vivo Activation—* We first engineered p53 variants that were specifically activated by HIV protease or the *B. anthracis* Lethal Factor (a metalloprotease). These effectors were novel because p53 does not ordinarily recognize or respond to them. Both proteases catalyze the hydrolysis of peptide substrates but do not overlap in sequence or conformational specificity (36, 37). Site-directed insertion mutagenesis was applied to replace p53 codons 360–369, which encode an unstructured spacer upstream of the C-terminal autoinhibitory domain (Fig. 1), with a sequence encoding the HIV protease substrate (p6, VSFNFPQIQL).

Similarly the sequence encoding the Lethal Factor substrate (LF10, KKVYYPPME (37)) was inserted at codon 364. The engineered p53 variants (designated p53/p6 and p53/LF10) and the wild-type p53 gene were separately co-expressed in *E. coli* with either HIV protease, LF, or no protease. The hexahistidine-tagged p53 proteins were purified by IMAC and analyzed by SDS-PAGE. The engineered protein migrated more quickly than the wild-type (at the same rate as the p53Δ30 control, which lacks its C-terminal domain), but only after co-expression with protease (data not shown). Equimolar quantities of the purified proteins were incubated with a double-stranded p53CON target sequence (25) conjugated to a near-infrared dye (IRD700-p53CON); the sequence-specific DNA binding activity of each was measured in an EMSA. The bands at the top of the gel reflect protein-DNA complexes, and their intensities are a measure of activation. Protease co-expression increased the apparent activity of the engineered p53 variants by ~30-fold for p53/p6 and a factor of >100-fold for p53/LF10 (Fig. 2a).

*In Vitro Protease Activation—* We confirmed that the proteases directly activated the engineered p53 variants through *in vitro* assays using purified proteins. The p53/p6, p53/LF10, and wild-type p53 proteins were separately expressed in *E. coli* and purified by IMAC; HIV protease was also separately expressed, mostly in inclusion bodies, sol-
ubilized in urea, purified by IMAC, and refolded (31). The purified p53 proteins were reacted with either purified HIV protease or Lethal Factor (EMD Biosciences); SDS-PAGE analysis confirmed the expected differences in migration after reactions with the proteases. EMSA analysis showed that Lethal Factor restored the activity of the engineered p53/LF10 variant to that of p53Δ30, whereas the HIV protease elicited more modest ~2-fold activation in p53/p6 (Fig. 2b). The latter activation factor is apparently worse than that of the comparable in vivo reaction, most likely because the pH of in vitro assay (7.6) was optimized for p53 rather than HIV protease (38).

High Throughput Protease Screen

Several high throughput p53 assays have been reported (see “Discussion”), and here we have demonstrated the utility of the p53/p6 variant within a semi-in vivo filter-lift screen (28). E. coli BL21(DE3) Gold/pLysS cells were separately transformed with p53/p6, p53Δ30, and wild-type p53 expression vectors. The transformed colonies were filter-lifted onto plates supplemented with 0.5 mM IPTG. Expression of the p53 genes was induced at room temperature for 4 h; the colonies were lysed by exposure to chloroform gas and probed with a radiolabeled p53CON oligonucleotide. Phosphorimaging analysis showed that the p53Δ30 protein exhibited ~2-fold greater activity (comparing photoluminescence/mm²) than the wild-type or p53/p6 proteins (Fig. 2c), consistent with published in vitro results (34).

Next we co-transformed E. coli BL21(DE3) Gold/pLysS with the p53/p6 expression vector and either PBAD-wild-type HIV PR-pCDF or PBAD-D25N-HIV PR-pCDF. The latter vectors are identical except that the HIV protease are largely insoluble when expressed in E. coli, so the visualization of both activities within individual colony remnants indicates the acute sensitivity of p53-based sensors.

Antibody Activation of p53

We also designed p53 variants that are activated by monoclonal antibodies rather than proteases. These sensors would have immediate utility in high throughput screens for antibodies and other binding effectors. Our strategy was to engineer monomeric p53 variants that are dimerized by antibodies. The exploitation of this second activation mechanism would further demonstrate the modularity of p53.
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To create a monomeric form of p53, we used site-directed deletion mutagenesis to remove the tetramerization and autoinhibitory domains (amino acids 324–393) (40). The resulting p53Δ68 gene was subcloned into pET28, thus fusing it to DNA encoding an N-terminal hexahistidine tag. We then replaced the pAb1801 epitope (wild-type p53 codons 46–55) of His––p53Δ68 with a sequence encoding the HA epitope, the HSV epitope, or an epitope to the Lethal Factor from B. anthracis (see "Experimental Procedures"). These p53 variants were purified and reacted with pAb1801 or the anti-HA, HSV, or LF monoclonal antibodies and an IRD700-labeled double-stranded p53 target sequence (p53CON). The antibody-p53-DNA complexes were separated from the free DNA by EMSA (Fig. 3b). The pixel intensities of bands containing antibody/engineered p53/p53CON complexes were divided by those of bands associated with the corresponding engineered p53/p53CON (no antibody) complex.

The purified p53Δ68 proteins were separately reacted with pAb1801 or the anti-epitope monoclonal antibodies and the IRD700–p53CON probe. The antibody-p53-DNA complexes were separated from the free DNA by EMSA (Fig. 3a). The p53Δ68 variant had an ~80-fold increase in activity upon the addition of pAb1801 Ab. p53-HA–Δ68 had an ~30-fold increase after adding the HA antibody, p53-HSV–Δ68 had an ~100-fold increase, and p53-LF(Ab)–Δ68 had a 3-fold increase in activity (Fig. 3b). We were not surprised to see two bands at the top of the gels, as both p53CON and the antibodies are capable of multimeric binding. We assayed our p53 variants at concentrations that were barely detectable in the absence of antibody and would have obtained even higher activation factors if we had employed the sensor at lower concentrations. The differences in the activation factors might be because of differences in the binding affinity of the antibody to the inserted tag. These values are significantly better than previously reported antibody sensors (14) and should enable assays with broader dynamic range.

**DISCUSSION**

We have designed p53 variants that are specifically activated by HIV protease, Lethal Factor, or monoclonal antibodies specific to the HA, HSV, and LF epitopes. These p53-based sensors are versatile with respect to both input molecular recognition and output signals. All of these inserted peptides differ significantly in amino acid sequence and conformation (Fig. 1a). HIV protease recognizes bent, hydrophobic peptides (36); Lethal Factor recognizes straight, basic peptides (37). Yet the p53/p6 and p53/LF10 proteins were specifically recognized, cleaved, and activated by HIV protease and Lethal Factor, respectively. We therefore believe that p53 could easily be reprogrammed for the detection of any protease or antibody. The latter is significant because modification-specific antibodies should enable p53-based high throughput screen for kinases, acetylases, and other protein-modifying activities.

With regard to applications, we showed here that p53 can be detected in EMSA assays and in high throughput colony lift assays. These results underscore the versatility of p53, because it is relatively difficult to control the amount of p53 expression within individual E. coli colonies. The wild-type p53 protein functions in vivo as a sensor of DNA damage, hypoxia, ribosome biogenesis, rNTP depletion, spindle damage, temperature shock, nitric oxide, and oncogene activation; these signals are mediated by an array of upstream regulatory proteins (41). In vivo p53 assays based on reporter gene activation have been developed in transgenic mammalian (42) and yeast (43) cells. The co-expression of p53-based sensors and engineered p53-binding proteins should similarly enable in vivo screens and selections for a wide variety of effectors.

The HIV protease-activated p53 variant also has potential as a therapy or "intracellular vaccine" for AIDS. Expression of the wild-type p53 protein normally leads to repression of transcription from the HIV-1 long terminal repeat (viral promoter; Ref. 44), as well as G1 growth arrest or premature apoptosis. The virus normally overcomes these pleiotropic effects by making a protein, Tat, that represses transcription of p53 (45). Expression of the HIV protease-activated variant in HIV-infected cells would have the following virtues as a gene therapy for AIDS. First, it is unlikely that a naturally occurring protein that requires activation by HIV-1-encoded factors will cause side effects. Second, p53 activity has graduated effects (repression of viral transcription, G1 growth arrest, apoptosis) that are less drastic than those of other "Trojan horse" therapies (8, 9). Third, these effects are mediated by cellular factors that inhibit viral replication, so it unlikely that HIV-1 could evolve immunity against the engineered p53.

We have also shown that p53 can display a variety of peptide sequences at two different locations. Previous workers have reprogrammed the effector dependence of N-WASP (17). We are therefore very optimistic about the prospects for the rational design of intrinsically unstructured proteins in general. An estimated 25–40% of all amino acid residues are thought to reside in unstructured domains (46), and many play important regulatory roles (16). We were initially reluctant to attempt rational design in the absence of a crystal structure but...
now encourage others to take advantage of the modularity and structural permissiveness of this functionally important class of proteins.

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