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Brief Communication

The substrate binding interface of alkylpurine DNA glycosylase AlkD

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ABSTRACT

Tandem helical repeats have emerged as an important DNA binding architecture. DNA glycosylase AlkD, which excises *N*3- and *N*7-alkylated nucleobases, uses repeating helical motifs to bind duplex DNA and to selectively pause at non-Watson–Crick base pairs. Remodeling of the DNA backbone promotes nucleotide flipping of the lesion and the complementary base into the solvent and toward the protein surface, respectively. The important features of this new DNA binding architecture that allow AlkD to distinguish between damaged and normal DNA without contacting the lesion are poorly understood. Here, we show through extensive mutational analysis that DNA binding and *N*3-methyladenine (3mA) and *N*7-methylguanine (7mG) excision are dependent upon each residue lining the DNA binding interface. Disrupting electrostatic or hydrophobic interactions with the DNA backbone substantially reduced binding affinity and catalytic activity. These results demonstrate that residues seemingly only involved in general DNA binding are important for catalytic activity and imply that base excision is driven by binding energy provided by the entire substrate interface of this novel DNA binding architecture.

1. Introduction

Genomic integrity is continuously threatened by chemical modifications caused by endogenous metabolites and environmental toxins. Alkylation, oxidation, and deamination produce a variety of single-base lesions with mutagenic and cytotoxic effects [1]. Each type of chemical alteration, however, is recognized by a DNA glycosylase that cleaves the *N*-glycosidic bond to liberate the damaged base and initiate base excision repair [2]. Recognition by most DNA glycosylases is achieved by penetration of the protein into the DNA duplex to exploit structural and/or energetic differences between normal and damaged bases pairs, and by flipping the damaged nucleobase into the enzyme active site [3].

The glycosylase AlkD selectively excises positively charged *N*3- and *N*7-methylpurines by a mechanism distinct from other monofunctional glycosylases [4–7]. AlkD is structurally unique, composed of six tandem helical ALK repeats that bear resemblance to HEAT motifs normally associated with protein interactions [8]. Crystal structures of AlkD in complex with DNA containing a 3mA mimetic and an abasic site analog revealed that, unlike other glycosylases, AlkD does not contact the damaged nucleotide, but rather anchors itself to the DNA duplex through interactions with the strand directly opposite the lesion and with regions of the damaged strand several nucleotides away from the lesion [7]. The enzyme-bound DNA is trapped in a distorted conformation in which the lesion is flipped toward the solvent and away from the protein, and the complementary nucleotide is flipped toward the protein surface. This arrangement is inconsistent with the typical catalytic mechanism of monofunctional glycosylases because it precludes a side-chain carboxylate from stabilizing the oxocarbenium intermediate formed during *N*-glycosidic bond cleavage or activating a water for nucleophilic attack at the anomeric C1′ carbon (Fig. 1) [9–14].

Alternatively, inhibition of AlkD catalyzed 7mG excision by methylphosphonate substitution suggests that the distorted DNA backbone conformation may allow a phosphate in close proximity to the lesion to provide electrostatic stabilization or nucleophilic activation through a substrate-assisted mechanism of catalysis [15], as previously observed for uracil excision from DNA by UDG [11,16,17]. Such a mechanism would suggest that without contacts to the lesion, AlkD must rely on enzyme–substrate binding energy to distort the DNA backbone into an autocatalytic conformation to promote base excision. Here, we demonstrate through mutational analysis that residues throughout the concave DNA binding surface, including residues distant from the lesion, affect binding and catalysis. These required, concerted interactions with multiple sites on both damaged and undamaged strands are consistent with a mechanism in which the DNA backbone must be remodeled into a catalytic conformation.

Abbreviations: 3d3mA, 3-deaza-*N*3-methyladenine; 3mA, *N*3-methyladenine; 7mG, *N*7-methylguanine; FAM, 6-carboxyfluorescein; THF, tetrahydrofuran.

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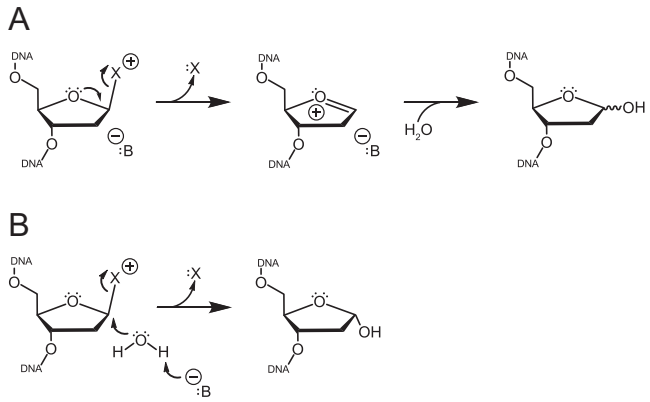

Fig. 1. Mechanisms of cationic lesion excision by monofunctional DNA glycosylases. Cleavage of the *N*-glycosidic bond liberates the damaged nucleobase ("X") and generates an abasic site. (A) Dissociative mechanisms utilize anionic protein side chains or DNA phosphate groups ("B") to directly assist bond breakage and to stabilize the resulting oxocarbenium intermediate. (B) Associative mechanisms employ a general base ("B") to activate a water for nucleophilic attack at the anomeric C1′ carbon.

2. Materials and methods

2.1. Protein purification

AlkD was purified by immobilized metal affinity, heparin affinity, and size exclusion chromatography steps as previously described [6]. AlkD mutants were generated by site-directed mutagenesis using a Quik-Change kit (Stratagene) and purified in the same manner as wild-type AlkD (Fig. S1).

2.2. Thermal melting

Structural integrity of AlkD mutants was verified by far-UV circular dichroism spectroscopy using a J-810 spectropolarimeter (Jasco) and a Peltier temperature controller (Jasco). Molar ellipticity was monitored at 222 nm as mixtures containing 10 μM enzyme, 20 mM Bis-Tris propane (pH 6.5), 100 mM NaCl, and 0.1 mM EDTA were heated at 2 °C/min in a 0.1-cm cell. Melting temperatures (T_m) were derived by fitting the data to the equation $\theta = 1/(1 + e^{(T_m - T)/k})$, where θ is molar ellipticity, T is temperature, T_m corresponds to the temperature at 50% denaturation, and k describes the cooperativity of the transition (Fig. S2).

2.3. DNA binding

DNA binding was monitored by changes in fluorescence anisotropy as enzyme was added to a 25-mer oligonucleotide duplex [d(GACCACTACACCXATTCCTAACAAC)/d(GTTGTTAGGAATYGGTGTAGTGGTC)-FAM] labeled with 6-carboxyfluorescein (FAM). Unmodified G·C-DNA contained X = G and Y = C, mismatched G·T DNA contained X = G and Y = T, and abasic THF·C-DNA contained X = THF and Y = C. Enzyme (0–30 μM AlkD-D113N and AlkD-R148A; 0–75 μM wild-type AlkD and all other mutants) was added to 50 nM FAM-DNA, 20 mM Bis-Tris propane (pH 6.5), 100 mM NaCl, 2 mM DTT, and 0.1 mM EDTA and incubated at 25 °C for 10 min. Fluorescence anisotropy measurements were recorded as previously described [6]. Equilibrium dissociation constants (K_d) were derived by fitting a two-state binding model to the data (Fig. S3).

2.4. Base excision from oligonucleotide substrate

Excision of 7mG from a 25-mer oligonucleotide duplex [d(GACCACTACACC(7mG)ATTCCTTACAAC)/d(GTTGTAAGGAATCGGTGTAGTGGTC)] was measured by autoradiography as previously described [6]. Reactions were performed at 37 °C and contained 20 μM enzyme (5 μM AlkD-D113N and AlkD-R148A), 2 nM DNA, and glycosylase buffer [50 mM HEPES (pH 7.5), 100 mM KCl, 10 mM DTT, and 2 mM EDTA]. Due to thermal instability, reactions containing AlkD-D113N (T_m = 30.7 °C) were also carried out at 25 °C to rule out inactivity due to protein unfolding. Second-order rate constants (k_{obs}) were obtained from single-exponential fits to the data (Fig. S4).

2.5. Base excision from genomic DNA substrate

Excision of 3mA and 7mG from methylated calf thymus DNA was measured by HPLC–MS/MS as previously described [18]. Reactions were performed at 37 °C for 1 h and contained 5 μM enzyme, 10 μg DNA, glycosylase buffer, and 0.1 mg/mL BSA. Due to thermal instability, reactions containing AlkD-D113N (T_m = 30.7 °C) were also carried out at 25 °C to rule out inactivity due to protein unfolding. In lieu of enzyme, controls contained 5 N HCl or 2 mM Bis-Tris propane (pH 6.5), 10 mM NaCl, and 0.01 mM EDTA.

3. Results and discussion

3.1. DNA binding architecture

Tandem helical repeats have emerged as an important and widespread structural feature among DNA binding proteins [8]. AlkD is composed of six antiparallel two-helix ALK motifs that stack into a short left-handed solenoid with a positively charged concave binding surface created by basic residues on each C-terminal helix (Fig. 2). Unlike other tandem helical repeats that bind nucleic acids, ALK motifs contact the backbone but not the nucleobases [8]. Sixteen residues on the concave surface of AlkD form electrostatic or hydrophobic contacts with phosphate or deoxyribose groups in substrate- and product-like complexes with DNA containing 3-deaza-*N*3-methyladenine (3d3mA) and tetrahydrofuran (THF), respectively (Fig. 2). The DNA in both complexes is markedly distorted. In the substrate-like complex, the 3d3mA·T base pair is sheared due to rotation of the thymine into the minor groove and toward the protein surface (Fig. 2). A nearly identical conformation is present in a complex containing DNA with a mismatched G·T base pair (PDB: 3JXY) [7]. In the product-like complex, both the thymine and the THF are fully extruded from the duplex, creating a single-base bulge in which base stacking is maintained by the flanking bases (Fig. 2).

In order to understand how this unique nucleic acid binding surface recognizes DNA damage, we mutated 10 of the 16 residues that contact the DNA in the crystal structures and measured DNA binding to 25-mer oligonucleotides containing a centrally located Watson–Crick G·C base pair, a G·T mismatch, or a THF·C abasic site; 7mG excision from the same 25-mer oligonucleotide; and 3mA and 7mG release from methylated genomic DNA. Wild-type AlkD binds G·C-, G·T-, and THF·C-DNA with weak (low micromolar) affinity typical of protein–DNA complexes involving only nonspecific backbone contacts (Fig. 3A and Table S1) [6]. Cleavage of 7mG from the same 25-mer oligonucleotide occurs at $1.2 \times 10^3\ M^{-1}\ s^{-1}$ (Fig. 3B and Table S2), while excision of 7mG and 3mA from methylated genomic DNA occurs 5-fold more slowly ($2.2 \times 10^2\ M^{-1}\ s^{-1}$) and 7-fold more rapidly ($8.0 \times 10^3\ M^{-1}\ s^{-1}$), respectively [18]. These rates of lesion removal are comparable to some 3mA glycosylases that extrude the damaged base into a nucleobase binding pocket during catalysis [19–22].

3.2. Damaged strand interactions

Six basic or neutral hydrophilic residues interact with the modified DNA strand. Three of these residues (Gln38, Thr39,

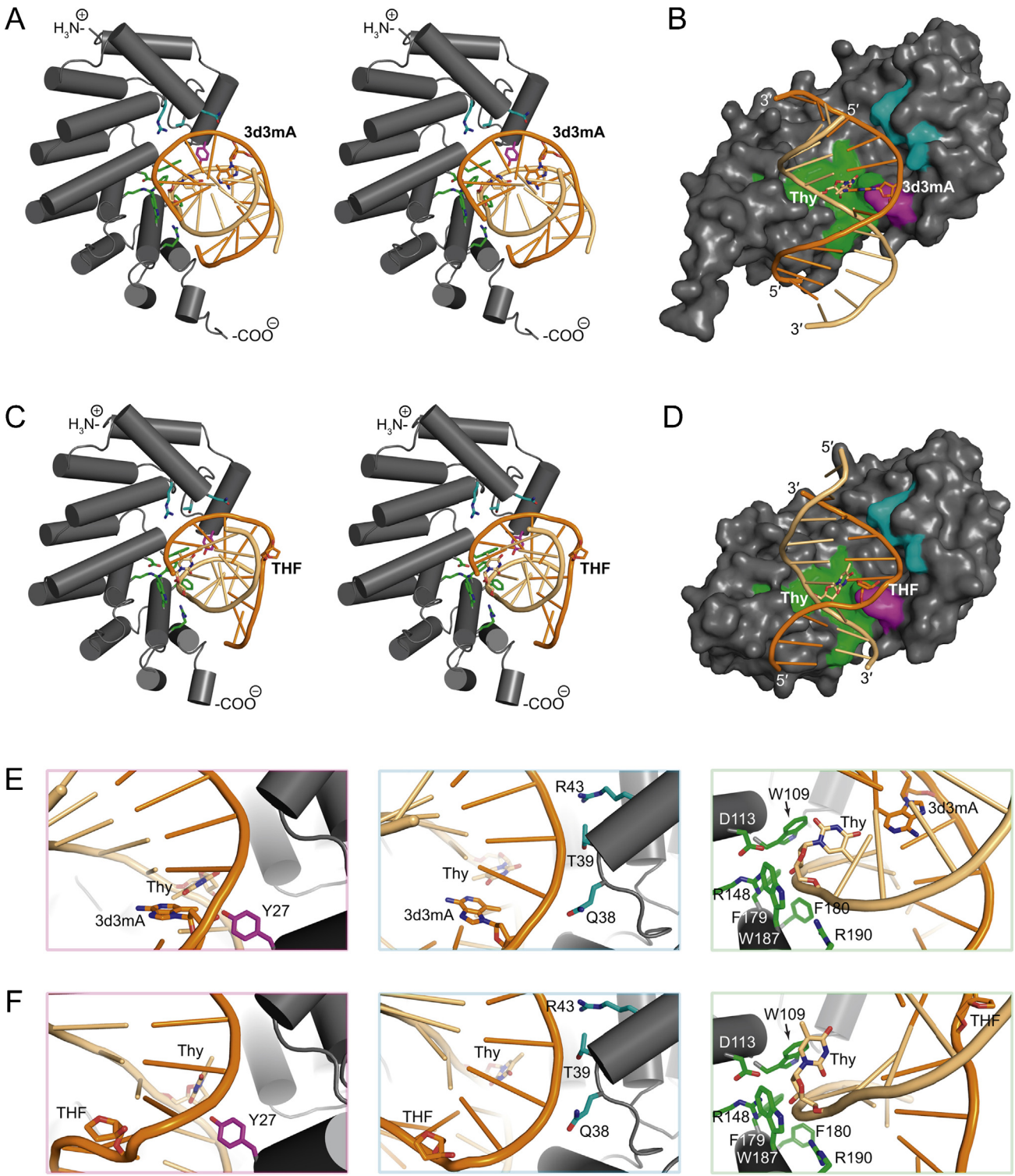

Fig. 2. Protein–DNA interactions on the concave surface of AlkD. (A and C) Stereodiagrams of AlkD–DNA interactions in substrate- (A, PDB: 3JX7) and product-like (C, PDB: 3JXZ) complexes containing 3-deaza-*N*3-methyladenine (3d3mA) and tetrahydrofuran (THF), respectively. (B and D) Surface representations of contacts in the substrate- (B) and product-like (D) complexes shown in panels A and C. (E and F) Close-up views of interactions in the substrate- (E) and product-like (F) complexes shown in panels A and C. In all panels, 3d3mA, THF, and the complementary thymidine are shown as sticks. Minor groove contacts (Tyr27), damaged strand contacts (Gln38, Thr39, and Arg43), and undamaged strand contacts (Trp109, Asp113, Arg148, Phe179, Phe180, Trp187, and Arg190) are colored magenta, cyan, and green, respectively. The damaged strand and the undamaged strand are colored bright orange and light orange, respectively.

and Arg43), clustered on the 3′ side of the damaged base, were mutated to aspartate or glutamate. As expected, electrostatic repulsion between the carboxylate side chains and the DNA backbone reduced binding affinity for all three oligonucleotide constructs by 2.2–11-fold (Fig. 3A and Table S1). Correspondingly, excision of 7mG from oligonucleotide DNA was slowed by 3.6–110-fold (Fig. 3B and Table S2), and release of 7mG from methylated genomic DNA was reduced by ≤2.5-fold (Fig. 3C and Table S3). Like wild-type AlkD, all mutants completely excised 3mA from genomic DNA. Despite the lack of contacts with the lesion, there is a correlation

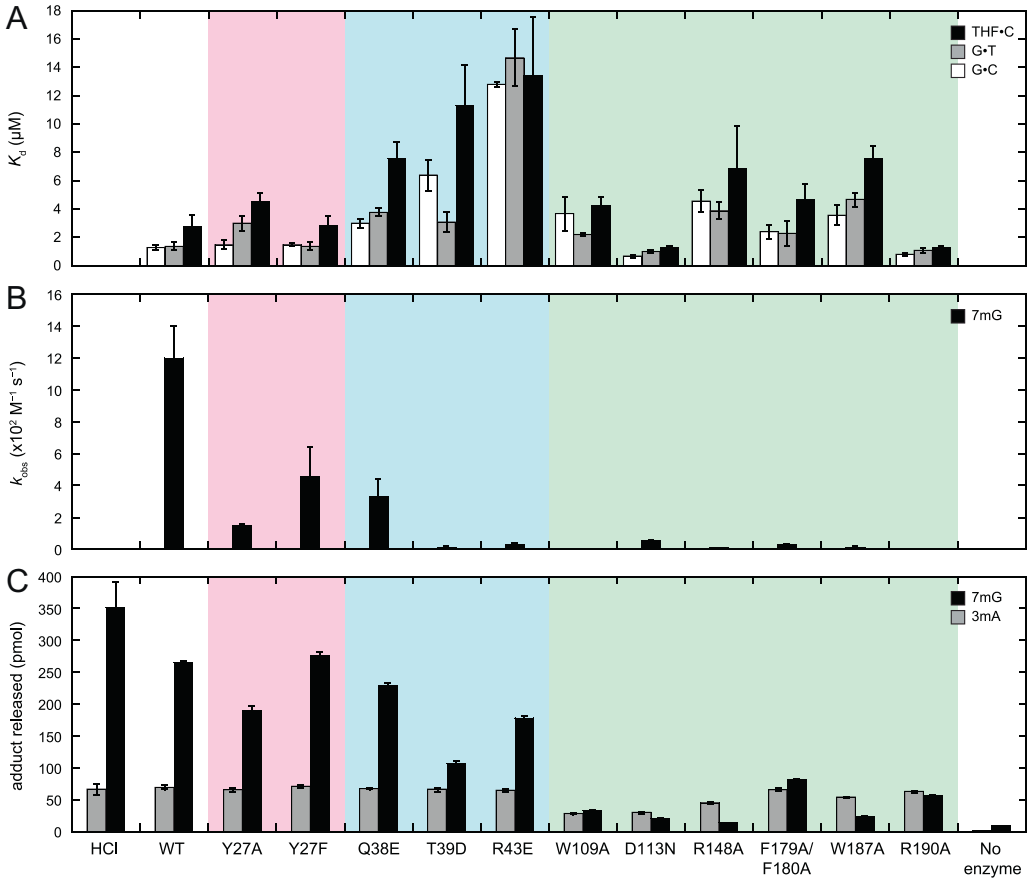

Fig. 3. DNA binding affinities and base excision activities of wild-type and mutant AlkD. (A) Equilibrium dissociation constants (K_d) for binding of FAM-labeled 25-mer oligonucleotide duplexes containing a centrally located G·C (white bars), G·T (gray bars), or THF·C (black bars). (B) Second-order rate constants (k_{obs}) for excision of 7mG (black bars) from a 25-mer oligonucleotide duplex. (C) 3mA (gray bars) and 7mG (black bars) released from methylated genomic DNA. HCl and no-enzyme controls represent the upper and lower limits for adduct removal. All panels show the averages and standard deviations from three experiments. Values are provided in Tables S1–S3. Mutants are colored in accordance with residues in Fig. 2.

between reduction in DNA binding and loss of base excision activity as a result of mutating residues contacting the damaged DNA strand.

3.3. Undamaged strand interactions

Ten basic or hydrophobic residues contact the unmodified DNA strand. Six of these residues (Trp109, Arg148, Phe179, Phe180, Trp187, and Arg190), which are located in or around a shallow, aromatic-rich cleft, were mutated to alanine. With the exception of the Arg190 → Ala mutation, all alanine substitutions decreased affinity for the three DNA substrates by 1.5–3.5-fold, while alanine substitution of Arg190 slightly increased affinity, most notably for THF·C-DNA (Fig. 3A and Table S1). This modest increase in binding affinity by AlkD-R190A is consistent with the THF-DNA complex structure, which suggests that removal of the Arg190 side chain would allow for optimized van der Waals and stacking interactions from Trp109 and Trp187 (Fig. S5). Irrespective of the type of interaction, the binding data confirms the importance of each of these residues in the concave surface. Likewise, excision of 7mG from oligonucleotide DNA by all mutants, including AlkD-R190A, was retarded by 37–360-fold (Fig. 3B and Table S2), and release of 3mA and 7mG from methylated genomic DNA was decreased by ≤2.4-fold and 3.2–20-fold, respectively (Fig. 3C and Table S3). Thus, the coordinated reduction of DNA binding and catalytic activity resulting from disrupting electrostatic interactions with the damaged strand extends to hydrophobic contacts with the undamaged strand. The increased DNA binding affinity and decreased lesion excision activity of AlkD-R190A are consistent with the use of binding energy to distort the DNA into a disfavored but catalytically competent conformation.

Asp113 does not contact the DNA in either crystal structure but does form a salt bridge with Arg148 at the center of the aromatic-rich cleft near the base opposite the lesion. Mutation of Asp113 has been shown previously to modestly strengthen DNA binding yet substantially slow lesion excision [5,6,18]. Relative to wild-type AlkD, AlkD-D113N binds all three oligonucleotide constructs 1.4–2.0-fold more tightly (Fig. 3A and Table S1), but excises 7mG from oligonucleotide substrate 21-fold more slowly (Fig. 3B and Table S2). Correspondingly, removal of 3mA and 7mG from methylated genomic DNA is decreased by 2.3-fold and 13-fold, respectively (Fig. 3C and Table S3). These seemingly contradictory phenomena have been attributed to reduced electrostatic repulsion between the carboxylate side chain and the DNA backbone but decreased thermal stability (Fig. S2) due to disruption of the salt bridge [6,7]. The latter could correlate with loss of the structural rigidity necessary to appropriately remodel the DNA backbone.

3.4. Minor groove interactions

A single bulky hydrophilic residue (Tyr27) inserted into the minor groove forms a hydrogen bond with the nucleobase on the unmodified strand immediately 3′ to the thymine opposite the damaged base. Tyr27 was mutated to alanine and phenylalanine to differentiate effects due to hydrogen-bonding and steric interactions. Phenylalanine substitution had no appreciable influence

on binding affinity for any of the three DNA constructs (Fig. 3A and Table S1), and likewise failed to alter levels of 3mA and 7mG released from genomic DNA (Fig. 3C and Table S3). Excision of 7mG from the oligonucleotide substrate was reduced by 2.6-fold (Fig. 3B and Table S2). Conversely, alanine substitution modestly decreased affinity for the oligonucleotide constructs containing a mismatched G·T base pair or an abasic THF·C site by 2.1-fold and 1.6-fold, respectively, but did not significantly affect binding of G·C-DNA (Fig. 3A and Table S1). Release of 3mA and 7mG from genomic DNA was decreased by 1.1-fold and 1.4-fold, respectively (Fig. 3C and Table S3), and excision of 7mG from oligonucleotide DNA was slowed by 7.7-fold (Fig. 3B and Table S2). While the small influences of the Tyr27 → Phe mutation are consistent with loss of the hydrogen bond observed in the crystal structures, the greater, albeit small, effects of the Tyr27 → Ala mutation suggest that the steric bulk of the aromatic ring also plays a role in Tyr27–DNA interactions.

4. Conclusions

We mutated ten residues on the DNA binding surface of AlkD and found that every mutation, regardless of location relative to the lesion, reduced the rate of 7mG excision from an oligonucleotide substrate. Most mutations also decreased cleavage of 7mG from a genomic DNA substrate, but few mutations altered cleavage of 3mA. Apparent changes in 3mA excision, however, were attenuated by substrate depletion, masking small to moderate changes in the rate of 3mA cleavage and obscuring possible alterations of substrate specificity. While aspartate or glutamate substitution of residues contacting the damaged strand at sites flanking the lesion had the greatest impact on DNA binding affinity, alanine substitution of residues interacting with the undamaged strand directly across from the lesion had the largest effect on catalysis. Mutation of Tyr27, the only residue that contacts a nucleobase, had only very modest influences on DNA affinity and lesion excision. These results support a mechanism of catalysis in which electrostatic interactions throughout the binding interface distort the DNA into a catalytically competent conformation. In the previously proposed autocatalytic single-base bulge [7], the positively charged and inherently labile alkylated lesion would be flipped out of the duplex through the major groove and into the proximity of a phosphate in the kinked DNA backbone, conceivably providing stabilization for the oxocarbenium intermediate formed upon cleavage of the *N*-glycosidic bond or facilitating activation of a water for nucleophilic attack at the anomeric C1′ carbon. Concomitantly, the base opposite the lesion would be flipped through the minor groove and retained in an aromatic-rich cleft, stabilizing the altered conformation of the DNA and extending the lifetime of the damaged base near the catalytic phosphate. We suggest that transient interrogating interactions between Tyr27 and nucleobase edges may provide additional sensitivity as AlkD scans double-stranded DNA for energetically unstable base pairs. Analogously, glycosylases that flip the lesion into a nucleobase binding pocket utilize DNA intercalating “plug” and “wedge” residues to prolong extrusion of the damaged base and to disrupt irregular base pairs, respectively [3].

Conflict of interest

The authors declare that there are no conflicts of interest.

Author contributions

B.F.E. oversaw the project; E.H.R. generated and purified AlkD mutants and performed oligonucleotide-based base excision assays, DNA binding assays, and thermal melting experiments; E.A.M. performed genomic DNA-based base excision assays; all authors analyzed data and wrote the paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.dnarep.2013.10.009.

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