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Induction of Topoisomerase I Cleavage Complexes by the Vinyl Chloride Adduct 1,N^6-Ethenoadenine*

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We used purified mammalian topoisomerases I (top1) and oligonucleotides to study top1-mediated cleavage and religation in the presence of a potent carcinogenic adduct, 1,N^6-ethenoadenosine (ϵA) incorporated immediately downstream of a unique top1 cleavage site. We found tha ϵA markedly enhanced top1 cleavage complexes when it was incorporated at the +1 position of the top1 cleavage. This enhancement was due to a reduction of the religation step of the top1 reaction. In addition, ϵA reduced the top1-mediated cleavage and decreased binding of the enzyme to DNA. We also studied the effects of the ϵA adduct on top1 trapping by camptothecin (CPT), a well known top1 inhibitor. CPT was inactive when ϵA was present at the +1 position. Alkylation of the top1 cleavage complex by 7-chloromethyl-10,11-methylenedioxycamptothecin (7-ClMe-MDO-CPT) was also blocked by the ϵA adduct. Altogether, these results demonstrate that the ϵA carcinogenic adduct can efficiently trap human top1 and mimic CPT effects. Normal hydrogen bonding of the base pairs immediately downstream from the top1 cleavage site is probably essential for efficient DNA religation and binding of camptothecins in the top1 cleavage complex.

Vinyl chloride is a potent carcinogen. Its metabolites are reactive species that can induce cyclic adducts in DNA. Four adducts have been characterized: the 1,N^2-ethenodeoxyguanosine (ϵG),[1] the N^2,3-ethenodeoxyguanosine, the 3,N^4-ethenodeoxycytidine (ϵC), and the 1,N^6-ethenodeoxyadenosine (ϵA) (1). These adducts can also be generated by other exogenous sources such as vinyl carbamate, ethyl carbamate, and other P450-mediated oxidized two-carbon compounds (2, 3). More recently, ϵA and ϵC have been detected in normal hepatocytes, suggesting their endogenous formation (4), probably through multiple reactive intermediates such as lipid peroxidation products (5). *In vivo* cytotoxicity and carcinogenic effects of etheno adducts have been linked to their mutagenic properties (6–9). For instance, ϵG causes G/A transitions and ϵdA causes A/C transversions *in vivo* (7, 9). When introduced into DNA, ϵA and ϵC are recognized and removed by human cell extracts at similar rates (10). Two separate DNA glycosylase activities have been reported for ϵA and ϵC excision (11), but the corresponding proteins have not been identified yet.

Topoisomerase I (top1) is important for DNA replication and transcription, because it can remove the torsional constraint along the DNA (12–14). Its role in DNA repair is less well established (15, 16). Mammalian top1 cleaves one strand of the DNA and remains covalently attached to the 3′-end of the transient break. This catalytic intermediate is referred to as the top1 cleavage complex. This reaction is reversible, and in normal conditions, only a small fraction of the cleaved DNA is detectable. Top1 inhibitors (poisons) such as camptothecin (CPT) increase (trap) top1 cleavage complexes by inhibiting the religation step (17, 18).

Both topoisomerase I and II can be trapped by DNA modifications such as mismatches, abasic sites, nicks, and gaps, when such lesions are in the vicinity of the enzyme cleavage site (19–22). In the present study, we used oligonucleotides containing an ϵA at the +1 position relative to the cleavage site and analyzed the effects on the top1-mediated DNA cleavage and religation and on top1 binding to DNA. We show for the first time that the carcinogenic adduct, ϵA, can trap top1 and mimic CPT effects. We also demonstrate that the ϵA adduct decreases top1 binding to DNA and the "on-rate" DNA cleavage. Finally, CPT activity was strongly inhibited when ϵA was in the immediate vicinity of a top1 cleavage site.

MATERIALS AND METHODS

Chemicals—High performance liquid chromatography-purified oligonucleotides were purchased from The Midland Certified Reagent Company (Midland, TX). α-^{32}P-Cordycepin 5′-triphosphate was purchased from NEN Life Science Products and polyacrylamide from Bio-Rad. CPT and 7-chloromethyl-10,11-methylenedioxy-20(*S*)-camptothecin (7-ClMe-MDO-CPT) were provided by Drs. Wani and Wall (Research Triangle Institute, Research Triangle Park, NC). Ten-millimolar aliquots of CPT or 7-ClMe-MDO-CPT were stored at −20° C, thawed, and diluted to 1 mM in dimethyl sulfoxide (Me_2SO) just before use.

Oligonucleotides Labeling and Annealing Procedures—3′ labeling was performed using terminal deoxynucleotidyl transferase (Stratagene, La Jolla, CA) with α-^{32}P-cordycepin as described previously (23). Labeling mixtures were subsequently centrifuged through a G-25 Sephadex column to remove excess of unincorporated nucleotide. Radiolabeled single-stranded DNA oligonucleotides were annealed to the same concentration of unlabeled complementary strand in 1 × annealing buffer (10 mM Tris-HCl, pH 7.8, 100 mM NaCl, 1 mM EDTA). Annealing mixtures were heated to 95° C for 5 min and slowly chilled overnight to room temperature.

Top1 Purification—Overexpression of the human recombinant top1 was performed in Sf9 insect cells using a baculovirus virus construct containing the top1 full-length cDNA (24). Nuclear extracts were from infected Sf9 cells 4 days after infection as described previously (20) and kept at −80° C before use. Human top1 was purified from nuclear extract using nickel-nitrilotriacetic acid-agarose beads (Qiagen, Santa Clarita, CA). 50 μl of beads were placed into microcentrifuge tubes and washed three times with 1 ml of wash buffer (50 mM Hepes, pH 7, 0.5 mM dithiothreitol, 10 mM $MgCl_2$, 3 mM $MnCl_2$, 50 mM KCl). 500 μl of nuclear extract were incubated with beads for 30 min at 4° C and

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[1] The abbreviations used are: ϵG, 1,N^2-ethenodeoxyguanosine; ϵC, 3,N^4-ethenodeoxycytidine; ϵA, 1,N^6-ethenoadenosine; top1, topoisomerases I; CPT, camptothecin; 7-ClMe-MDO-CPT, 7-chloromethyl-10,11-methylenedioxycamptothecin.

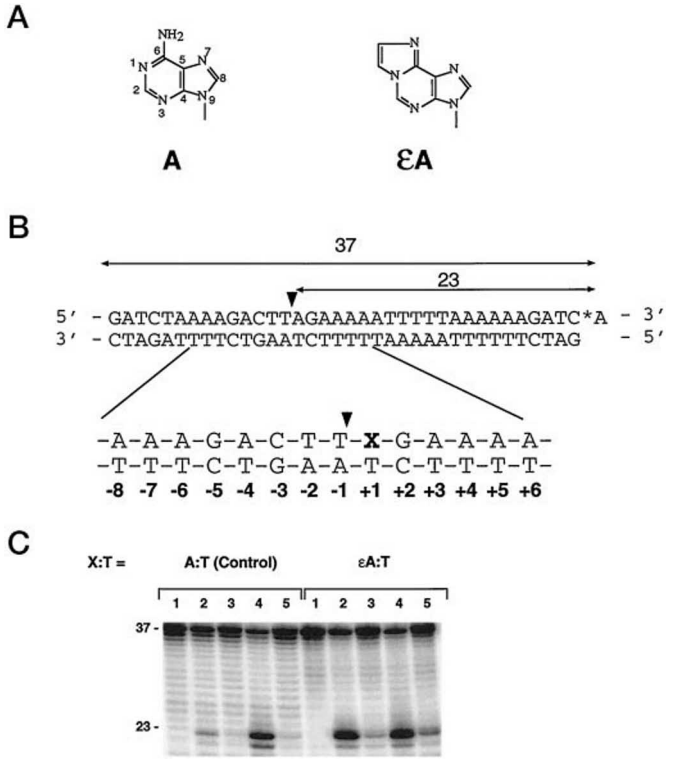

FIG. 1. **Reversible trapping of top1 cleavage complexes by ϵA incorporation at the +1 position of an oligonucleotide containing a single top1 cleavage site.** *A*, structure comparison between adenine and the bulky adduct 1,N^6-ethenoadenine (ϵA). *B*, Tetrahymena hexadecameric rDNA sequence with a strong top1 cleavage site was labeled with ^{32}P-cordycepin (*A) at the 3′ terminus of the scissile (*upper*) strand. *X* represents the +1 position of the scissile strand where ϵA was incorporated. The *arrowhead* corresponds to the top1 cleavage site. *C*, oligonucleotides with A (*Control*) or ϵA at the +1 position were reacted as follows: *Lanes 1*, DNA alone; *lanes 2* and *3*, +top1; *lanes 4* and *5*, +top1 + 10 μM CPT. Reactions were performed at 25° C for 30 min and stopped either immediately with 0.5% SDS (*lanes 2* and *4*) or after treatment with 0.5 M NaCl (final concentration) for an additional hour at 25° C before addition of 0.5% SDS (*lanes 3* and *5*). *Numbers* indicate product sizes (see *B*).

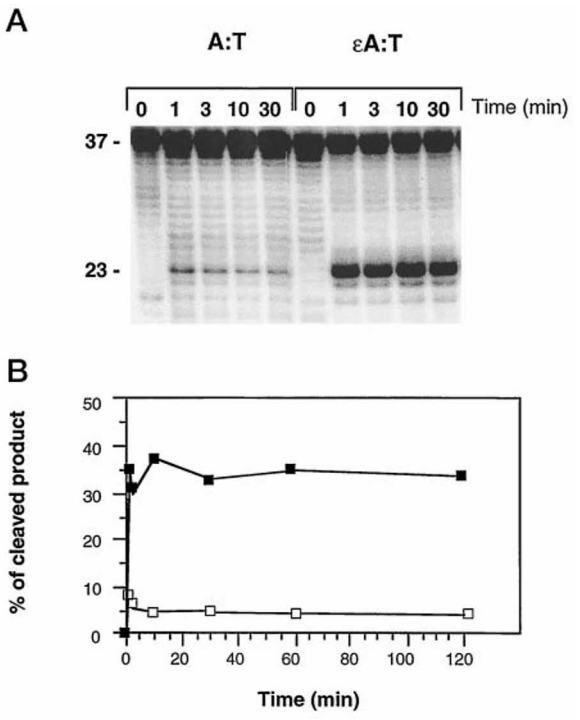

FIG. 2. **Kinetics of formation of ϵA-mediated top1 cleavage complexes.** *A*, oligonucleotides containing either A or ϵA at the +1 position relative to the top1 cleavage site (see Fig. 1*B*) were incubated with purified human top1. Reactions were stopped with 0.5% SDS at the indicated times. *B*, quantitation of the gel presented in *A*.

washed two times with 300 μl of the wash buffer. Insect cells top1 was eluted with wash buffer containing 40 mM imidazole. Human recombinant top1 was eluted with wash buffer containing 300 mM imidazole and dialyzed 3 h with 30 mM potassium phosphate buffer (pH 7), 0.1 mM EDTA, 5 mM dithiothreitol. Bovine serum albumin (0.2 mg/ml) and glycerol (30% v/v) were added to the purified top1, and aliquots were stored at −20° C.

Top1 Reactions—DNA substrates (approximately 50 fmol/reaction) were incubated with 5 units of calf thymus or with human recombinant top1 usually for 30 min at 25° C with or without drug in standard reaction buffer (10 mM Tris-HCl, pH 7.5, 50 mM KCl, 5 mM $MgCl_2$, 0.1 mM EDTA, 15 μg/ml bovine serum albumin). Reactions were stopped by adding either sodium dodecyl sulfate (SDS) (final concentration 0.5%) or NaCl (0.5 M for 30 min at 25° C followed by addition of 0.5% SDS for standard reactions or 0.35 M NaCl at 4° C for kinetics of reversal.

Gel Electrophoresis and Analysis of Cleavage Products—3.3 volumes of Maxam Gilbert loading buffer (98% formamide, 0.01 M EDTA, 1 mg/ml xylene cyanol, and 1 mg/ml bromphenol blue) were added to the reaction mixtures before loading. 16% denaturing polyacrylamide gels (7 M urea) were run at 40 V/cm at 50° C for 2–3 h and dried on 3MM Whatman paper sheets. Imaging and quantitations were performed using a PhosphorImager (Molecular Dynamics, Sunnyvale, CA).

DNA Binding Assay—3′-Labeled DNA substrates (approximately 25 fmol/reaction) were incubated in the presence of increasing concentrations of yeast Y727F mutant (final volume of 20 μl) in 50 mM Tris-HCl pH 7.5 (25) and 50 ng of double-stranded poly(dI-dC) DNA (Sigma) for 5 min at room temperature. Ten microliters of 3 × neutral loading buffer (10 mM Tris-HCl, pH 7.5, 30% glycerol, 0.1% bromphenol blue) was added to each reaction before loading into a 6% native polyacrylamide gel in 0.25 × TBE. Electrophoresis was for 2 h at 100 V in 0.25 × TBE buffer (25 mM Tris, 22.5 mM boric acid, 0.25 mM EDTA). Imaging and quantitations were performed using a PhosphorImager (Molecular Dynamics, Sunnyvale, CA).

RESULTS

Top1 Is Reversibly Trapped by ϵA at the +1 Position of a Top1 Cleavage Site—In this study we have investigated the effect of ϵA on top1 activity *in vitro*. As shown in Fig. 1*A*, the ϵA bulky adduct differs from adenine by the presence of an additional ring resulting from a cyclization reaction of reactive species such as the vinyl chloride metabolite, chloroacetaldehyde (26). We used purified oligonucleotides derived from the Tetrahymena ribosomal DNA sequence (27) and analyzed the effects of ϵA incorporation at the +1 position of the scissile strand (*X* in Fig. 1B) on top1-mediated DNA cleavage and religation using purified recombinant human enzyme. As shown in Fig. 1*C*, incorporation of ϵA led to approximately 6-fold increase of top1-mediated cleavage complexes (compare *lanes 2*). Top1 cleavage/religation equilibrium can be shifted toward religation by increasing the salt concentration in the reaction (28). In the case of the ϵA oligonucleotide, 0.5 M NaCl was able to reverse the top1-mediated cleavage complexes (Fig. 1*C*, *left panel*, *lane 3*).

Previous studies indicated that CPT interacted with the +1 base immediately 3′ to the top1 cleavage site (29) and increased the top1 cleavage complex (compare *lanes 2* and *4* in the control panel) by inhibiting the religation step of the reaction (12, 17, 30). In the case of the ϵA oligonucleotide, CPT did not enhance top1-mediated DNA cleavage further (Fig. 1*C*, compare *lanes 2* and *4* on the *right panel*), and the reaction was still reversible in the presence of 0.5 M NaCl (*lane 5*, *right panel*).

These results demonstrate that the carcinogenic adduct ϵA incorporated at the +1 position of a top1 cleavage site reversibly traps top1.

Kinetics of Top1 Trapping by ϵA—We next compared the kinetics of top1 cleavage complex formation between the con-

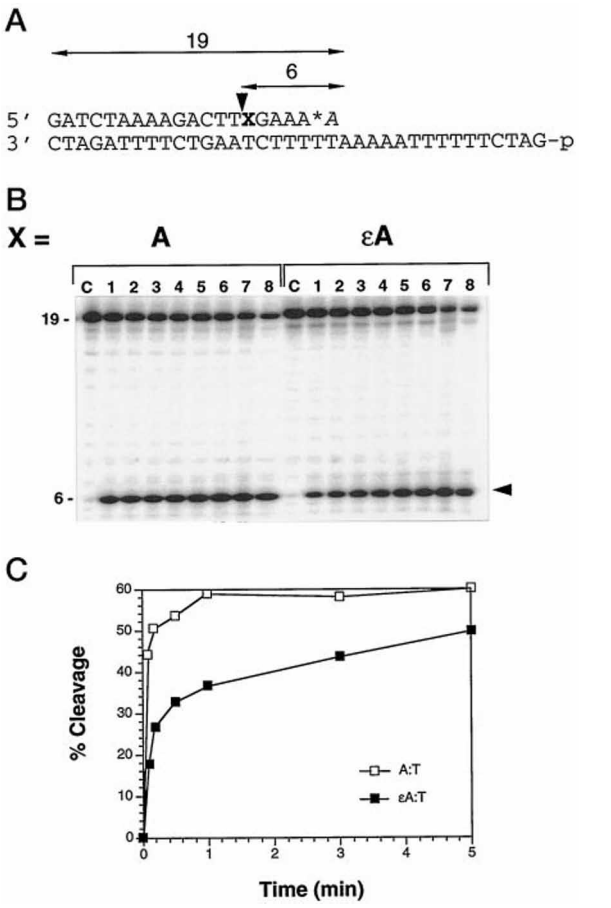

FIG. 3. **ϵA:T at the +1 position of top1 suicide substrates decreases the cleavage on-rate.** *A*, scissile strands with either A or ϵA at the +1 position were 3′-end-labeled and annealed to the normal 36-mer bearing a phosphate at the 5′-end. *B*, oligonucleotides were reacted at 25° C with purified top1 for different times (*lanes 1–8*: 5 s, 10 s, 30 s, 1 min, 3 min, 5 min, 10 min, and 30 min, respectively) before addition of 0.5% SDS (final concentration). *C*, gels were quantified using a PhosphorImager, and results were plotted as a function of time.

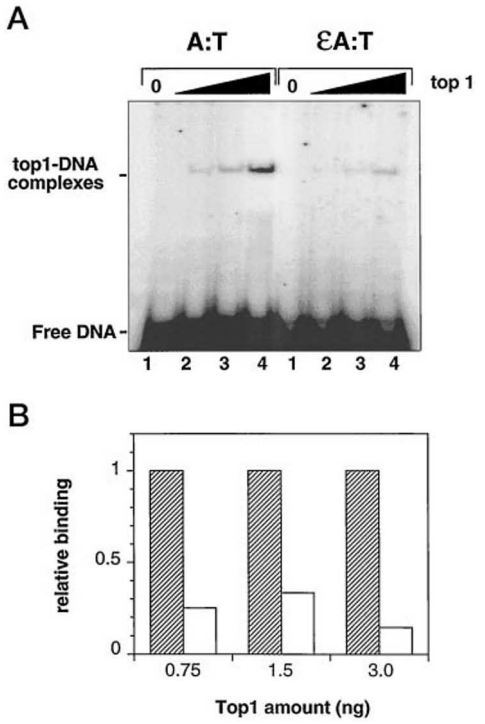

FIG. 4. **ϵA at the +1 position decreases top1 binding.** *A*, approximately 25 fmol of 3′-end-labeled oligonucleotides with either A (A:T) or ϵA (ϵA:T) at the +1 position (see Fig. 1*B*) were incubated with increasing amount of purified Y727F yeast mutant top1 for 5 min at 25° C. *Lanes 1–4* correspond to 0, 0.75, 1.5, and 3.0 ng of the yeast mutant top1, respectively. Equal counts/min were loaded on a 6% native polyacrylamide gel in 0.25 × TBE, and top1·DNA complexes were separated from free DNA at 100 V for 2 h. *B*, top1·DNA complexes were quantified from the dried gel shown in *A* using a PhosphorImager. For each concentration of enzyme, top1 binding to ϵA:T was calculated relative to the A:T (control) oligonucleotide (binding of top1 to the control oligonucleotide was normalized to 1).

trol oligonucleotide (A:T) and the ϵA-containing oligonucleotide (ϵA:T) to investigate whether reversible trapping could be further enhanced by increasing the reaction time. As shown in Fig. 2*A*, cleavage complexes were formed within the first minute of incubation for both the normal and ϵA oligonucleotides, and no further increase was detected. Instead, a slight decrease of the cleavage complexes was detected with longer incubation, probably resulting from a decrease of the enzyme activity. In accordance with the results presented in Fig. 1*C*, the plateau value was 5–6-fold higher when ϵA was present at the +1 position (Fig. 2*B*). These results demonstrate that the reversible trapping of top1 by ϵA probably corresponds to an equilibrium that is reached quickly once top1 is added to the reaction.

ϵA at the +1 Position Inhibits the Formation of Top1-mediated DNA Cleavage—Because top1-mediated DNA cleavage/religation is an equilibrium process, reversible trapping of the enzyme by ϵA could possibly result from either an increase of the cleavage (on-rate) or/and a decrease of the religation ("off-rate"). In the following experiments, we separately investigated the effects of ϵA on each step of the top1 reaction. We first studied the DNA cleavage formation in "suicide" oligonucleotides containing either A or ϵA at the +1 position relative to the top1 cleavage site (see Fig. 3*A*). Under these conditions, top1-mediated cleavage was examined under single turnover conditions (25, 30). Once top1 cleaves the DNA, it remains bound to the 3′-end of the scissile strand in a covalent complex (suicide complex), and the 3′-labeled 6-mer distal product is released (Fig. 3*B*, *arrowhead*). In our reactions, the 5′-end of the nonscissile strand was phosphorylated prior to annealing to avoid formation of recombination products (20, 23). The kinetics experiment presented in Fig. 3*B* show a marked difference in the on-rate reaction between the two suicide substrates. Cleavage was slower in the oligonucleotide containing an ϵA at the +1 position than in the control (Fig. 3*C*). The apparent cleavage rate constant (k_{cl}) was calculated. Cleavage was normalized to the end point value (*lanes 8* in Fig. 3*B*) of 72 and 78% for the A:T (*open squares*) and ϵA:T (*closed squares*) oligonucleotide, respectively, and k_{cl} was determined by fitting the data to the equation $(100 - \%Cl_{norm}) = 100\ e^{-k_{cl}t}$ (31). The k_{cl} for the ϵA-containing substrate was approximately 3-fold less than the control (0.047 s^{-1} *versus* 0.15 s^{-1}). These results indicate that the top1-mediated DNA cleavage rate (on-rate step) is reduced by the presence of ϵA at the +1 position of a top1 cleavage site.

ϵA at the +1 Position Inhibits Noncovalent Top1 Binding to DNA—To further determine whether presence of ϵA altered the top1-DNA interaction, DNA binding assays were performed. For this purpose, we used the catalytically inactive yeast top1 in which the active tyrosine in position 727 has been mutated to a phenylalanine (Y727F). This enzyme does not perform cleavage, but is still able to bind to the DNA (32, 33). We incubated 3′-labeled oligonucleotides containing either A (A:T) or ϵA (ϵA:T) at the +1 position in the presence of increasing amount of the yeast mutant top1 (Fig. 4). Y727F top1 was able to bind to both substrates, which resulted in the appearance of a slow migrating band corresponding to top1·DNA complexes in

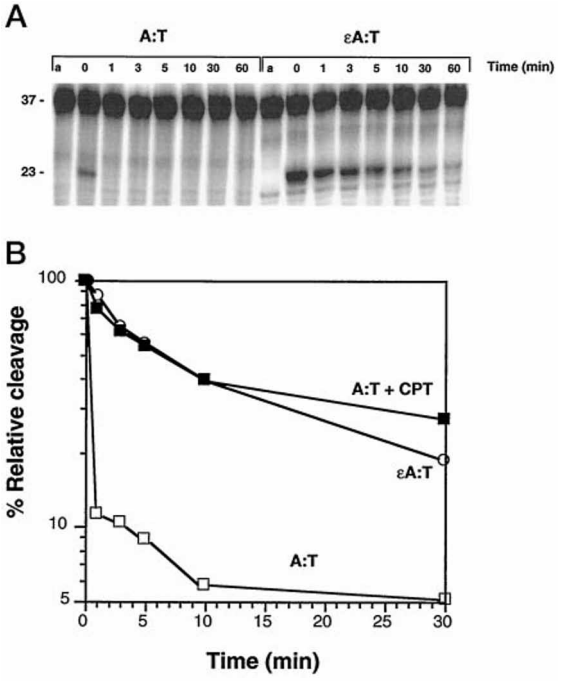

FIG. 5. **ϵA incorporated at the +1 position decreases the kinetics of religation of top1-induced DNA cleavage complexes.** 3′-End-labeled oligonucleotides with either an A (A:T) or ϵA at the +1 position (see Fig. 1*B*) were reacted with purified human top1. *A*, kinetics of religation were performed in the absence of CPT. DNA substrates (*lanes a*) were incubated with purified top1 for 15 min at 25° C. Reactions were then either stopped immediately with 0.5% SDS (*lanes 0*) or reversed at 4° C by adding 0.35 M NaCl (final concentration) for the indicated times before addition of 0.5% SDS. *B*, quantitation of the gel presented in *A*. Percentage of cleavage products were normalized relative to time 0. □, A:T oligonucleotide; ○, ϵA:T oligonucleotide; ■, inhibition of religation by CPT (10 μM) with the A:T oligonucleotide (not shown in *A*).

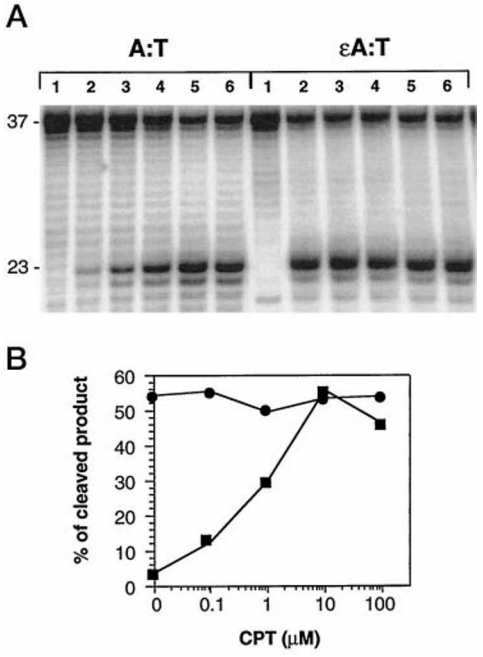

FIG. 6. **ϵA at the +1 position prevents to action of CPT.** *A*, 3′-end-labeled oligonucleotides with either A (A:T) or ϵA (ϵA:T) at the +1 position (see Fig. 1*B*) were incubated for 15 min at 25° C with purified top1 in the presence of increasing concentration of CPT before addition of 0.5% SDS. *Lanes 1*, DNA alone; *lanes 2*, +top1; *lanes 3–6*, +0.1, 1, 10, and 100 μM CPT, respectively. *B*, quantitations of the cleavage products in *A* using a PhosphorImager. Percentage of cleavage products was plotted as a function of CPT concentration. ■, A:T (control) oligonucleotide; ●, ϵA:T oligonucleotide.

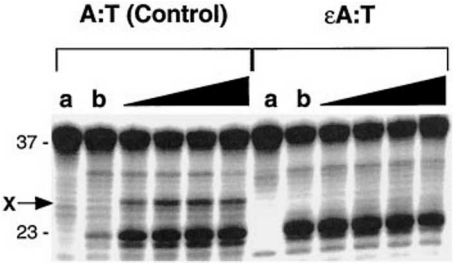

FIG. 7. **ϵA at the +1 position prevents top1-mediated DNA alkylation by 7-chloromethyl-10,11-methylenedioxycamptothecin.** 3′-End-labeled oligonucleotides with A:T or ϵA:T at the +1 position (see Fig. 1*B*) were incubated with human purified top1 for 1 h at 25° C in the presence of increasing concentrations of 7-ClMe-MDO-CPT. *Lanes 1*, DNA alone; *lanes 2*, +top1; *lanes 3–6*, +0.1, 1, 10, and 100 μM 7-ClMe-MDO-CPT, respectively. The *Arrow* (*X*) indicates the alkylated DNA product (29).

native polyacrylamide gels (Fig. 4*A*). Top1 binding to the ϵA-containing substrate was expressed relative to the binding to the control oligonucleotide (which was set to 1), and the ratio was determined for each concentration of enzyme (Fig. 4*B*). Top1 binding to the oligonculeotide with ϵA at the +1 position was reduced by approximately 4–5-fold compared with the control DNA. These results demonstrate that top1 binding is decreased by the presence of ϵA at the +1 position of the top1 site. They also suggest that reduction of the top1-mediated DNA cleavage on-rate (Fig. 3) is probably due to reduced binding of the enzyme to DNA.

ϵA Incorporation Mimics CPT Effects—Because the above data indicated that reduced top1 cleavage could not be responsible for top1 trapping by ϵA, we studied the influence of ϵA on the religation step (Fig. 5). For this purpose, we first incubated the normal and ϵA oligonucleotides (see Fig. 1*B*) with purified top1 for 15 min at 25° C to reach cleavage equilibrium (see Fig. 2). Religation was then studied after addition of 0.35 M NaCl. These religation experiments were performed at 4° C to better follow religation kinetics (Fig. 5*A*). Under these conditions, religation is slower than at 37° C (28). Religation was markedly decreased with the ϵA:T substrate as compared with the control oligonucleotide (Fig. 5*A*). As a comparison, we used the control oligonucleotide in the presence of 10 μM CPT. CPT is known to increase top1 cleavage complexes by inhibiting religation (17, 18). Cleavage products were quantitated and plotted as a function of time after salt addition (Fig. 5*B*). The kinetics of religation for the ϵA-containing substrate and the control oligonucleotide in the presence of CPT were comparable (Fig. 5*B*, compare *open circles* and *closed box*). These results demonstrate that reversible trapping of top1 by ϵA is due to an inhibition of the religation step of the top1 reaction.

Lack of Effect of CPT in the Oligonucleotide with ϵA at the +1 Position—As shown in Fig. 1*C*, CPT did not increase further top1-mediated DNA cleavage when ϵA was present at the +1 position of the top1 site. We investigated this further by using different CPT concentrations (Fig. 6). Whereas CPT was active even at low concentration (0.1 μM) in the control oligonucleotide (A:T), it did not increase top1-mediated cleavage even at high concentration in the ϵA oligonucleotide (Fig. 6*A*, compare *lanes 2* and *4* on the *right panel*). These results demonstrated that presence of ϵA at the +1 position relative to the top1 cleavage site prevents CPT activity.

ϵA at the +1 Position Prevents Alkylation of Guanine N3 by 7-ClMe-MDO-CPT—Because CPT has been reported to interact directly with the +1 base from the top1 cleavage site (29), we tested whether the lack of effect of CPT on top1 cleavage

was associated with alterations of the drug with the ϵA. For this purpose, we used the alkylating CPT, 7-ClMe-MDO-CPT. This drug alkylates the N3 position of the +1 guanine or adenine in the presence of top1 (29, 34). As reported previously, in the control oligonucleotide, 7-ClMe-MDO-CPT stimulated top1 cleavage complexes (Fig. 7, compare *lane b* with other lanes in the control panel) and formed the alkylated product that can be detected as a retarded band in denaturing polyacrylamide gel (Fig. 7, *arrow*). By contrast, when ϵA was incorporated at the +1 position, no increase of DNA cleavage was detectable with 7-ClMe-MDO-CPT. Moreover, the alkylation product was not detectable regardless of the concentration of 7-ClMe-MDO-CPT used. These results suggested that the lack of CPT activity when ϵA was present at the +1 position relative to a top1 cleavage site might be related to the altered structure of the +1 base pair.

DISCUSSION

In this study, we report for the first time that a potent carcinogenic adduct, ϵA can trap eukaryotic top1. ϵA incorporation results in altered base pairing with the thymine on the opposite DNA strand. Circular dichroism analysis demonstrates that the presence of the extra 4-membered ring suppresses the two hydrogen bonds (35). Our observation that ϵA can reversibly trap top1 is consistent with previous observations indicating that base mismatches at the +1 position can enhance top1 cleavage complexes (19, 36).

Reduced religation of top1-cleavable complexes appears to be the mechanism by which ϵA traps top1. Thus, carcinogenic adducts can mimic CPT effects. Once the DNA is cleaved by top1, perfect positioning of the +1 base is probably required for optimal top1-mediated DNA religation. This positioning closely depends on the hydrogen bonding of the +1 base pairs. True mismatches such as A:A base pairing or uracil misincorporation leading to wobble base pairing such as U:C or U:G also increase top1 cleavage complex formation, whereas U:A has no effect (19). Thus, any modification of the hydrogen bonding would potentially affect the religation (off-rate) of the top1 reaction.

We also found that binding and subsequent cleavage of the ϵA-containing DNA was significantly reduced. The activity of other DNA processing enzymes such as *Nhe*I or DNA polymerases has also been shown to be reduced by the presence of ϵA adducts (35, 37). In our system, top1 was still able to cleave the DNA next to the ϵA and cleavage was globally enhanced. This demonstrates that inhibition of religation by ϵA is the predominant mechanism responsible for the increase of top1-mediated cleavage complexes.

CPT has been shown to trap top1 cleavage complexes probably by interacting with the +1 base immediately downstream of the top1 cleavage site (29). Two models for CPT stacking to the +1 base have been proposed recently (16, 39). However, no crystal structure of the top1·DNA complex in the presence of CPT is available yet. In this study, we found that the effect of CPT was not detectable when ϵA was incorporated at the +1 position. Moreover, we could not detect alkylation of the DNA in the top1 cleavage complex by 7-ClMe-MDO-CPT when ϵA was next to the top1 cleavage site. Thus, ϵA at the +1 position prevents CPT interaction. This could be due to altered base pairing at the +1 position (19). Such base pairing might be important for optimum CPT interaction (stacking with the +1 base pair) within the top1-DNA complex (16, 39).

In conclusion, this study indicates that carcinogenic adducts generated from vinyl chloride and other industrial by-products can trap top1 and mimic CPT effects. This trapping might be part of the cell death pathways or repair mechanisms resulting from these lesions.

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