Podophyllotoxin as a Probe for the Colchicine Binding Site of Tubulin

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The binding of [3H]podophyllotoxin to tubulin, measured by a DEAE-cellulose filter paper method, occurs with an affinity constant of $1.8 \times 10^{10} \text{ M}^{-1}$ (37°C at pH 6.7). Like colchicine, $-0.8 \text{ mol of podophyllotoxin are bound per mol of tubulin dimer}$, and the reaction is entropy-driven (43 cal deg$^{-1}$ mol$^{-1}$).

At 37°C the association rate constant for podophyllotoxin binding is $3.8 \times 10^8 \text{ h}^{-1}$, 10 times higher than for colchicine; this is reflected in the activation energies for binding which are 14.7 kcal/mol for podophyllotoxin and 20.3 kcal/mol for colchicine. The dissociation rate constant for the tubulin-podophyllotoxin complex is 1.9 h$^{-1}$, and the affinity constant calculated from the ratio of the rates is close to that obtained by equilibrium measurements.

Podophyllotoxin and colchicine are mutually competitive inhibitors. This can be ascribed to the fact that both compounds have a trimethoxyphenyl ring and analogues of this region do not bind, it is concluded that both podophyllotoxin and colchicine are competitive inhibitors of the tubulin-podophyllotoxin complex.

Tropolone, which inhibits colchicine binding competitively, has no effect on the podophyllotoxin/tubulin reaction. Conversely, podophyllotoxin does not influence tropolone binding. Moreover, the tropolone binding site of tubulin does not show the temperature and pH lability of the colchicine and podophyllotoxin domains, hence this lability can be ascribed to the trimethoxyphenyl binding region of tubulin.

Since podophyllotoxin analogues with a modified B ring do not bind, it is concluded that both podophyllotoxin and colchicine each have at least two points of attachment to tubulin and that they share one of them, the binding region of the trimethoxyphenyl moiety.

Several classes of compounds are thought to interfere with microtubule-dependent cell functions because they bind to tubulin, the subunit of microtubules (1-3). They include colchicine, the Vinca alkaloids, such as vinblastine and vincristine, and podophyllotoxin. Although all of these compounds disaggregate microtubules, the Vinca alkaloids bind at a site that appears to be unrelated to the colchicine binding site (3-6). On the other hand, podophyllotoxin inhibits colchicine binding competitively (5-10), and this has been ascribed to the fact that both compounds possess a trimethoxyphenyl ring (7).

Nevertheless, there are important differences between these ligands. Thus, the tropolone moiety is an attachment point for colchicine to tubulin (7), and podophyllotoxin is devoid of this ring. Secondly, colchicine binds slowly, requiring $1/2 \text{ h}$ to attain equilibrium at 37°C (3, 5-9) and is reversible with difficulty (2, 5, 10), whereas podophyllotoxin is reported to bind and dissociate more rapidly (9, 10). These differences made it difficult to envisage a mechanism for the apparent competition between these two ligands for the binding site and led us to compare some of the kinetic and thermodynamic parameters for their binding as well as to specify the structural requirements that are shared or are different in these two compounds.

**EXPERIMENTAL PROCEDURES**

**Methods**

**Protein Purification**—Tubulin was purified from rat brains in PMG buffer" (10 mM sodium phosphate, pH 6.7; 10 mM MgCl$_2$, 10$^{-4}$ M GTP) by the procedure of Weisenberg et al. (11), except that DEAE-cellulose was used instead of DEAE-Sepharose. In some experiments we used the polymerization method described by Shelenkis et al. (12) or a procedure which combined both of the methods: after one or two cycles of polymerization of rat brain tubulin (12), the protein was depolymerized in PMG buffer at 0°C for 20 min, applied to a DEAE-cellulose column and eluted in the usual fashion (11). Tubulin thus prepared had the highest colchicine and podophyllotoxin binding activity as judged by the number of moles of ligand bound per mole of protein. The purified protein was stored at $-20°C$ in PMG buffer containing 1 M sucrose. The purity of tubulin was checked by polyacylamide gel electrophoresis in 0.1% sodium dodecyl sulfate according to Weber and Osborn (13). Gels contained 5% acrylamide and 0.2% bisacrylamide and were run in phosphate buffer (pH 7.1) at 23°C.

Protein concentrations were determined by the method of Lowry et al. (14), using bovine serum albumin as a standard.

Fluorescence was measured in the thermostated chamber of an Hitachi-Perkin-Elmer MFP-3 spectrofluorometer with excitation and emission wavelengths of 353 and 400 nm for colchicine, and 350 and 410 nm for tropolone.

**Incubation Procedure**—The incubation medium contained PMG buffer plus tubulin and [3H]podophyllotoxin of known specific activity or other ligands. Tubulin was kept at 0°C, and two min before the experiments it was brought to the appropriate temperature. In some experiments, when the tubulin concentration was lower than $1 \times 10^{-7}$ M, crystalline bovine serum albumin (0.1%) was added. The reaction was stopped by rapidly cooling the tubes to 0°C.

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assay was performed within 10 min after stopping the reaction. Colchicine binding was evaluated by the filter disc method of Weisenberg et al. (11), modified by Williams and Wolff (15) or by the fluorescence method of Bhattacharyya and Wolff (7). Tropolone binding was determined by fluorescence enhancement occurring in the presence of tubulin (7). Colcemid binding was determined by a method identical to that used for podophyllotoxin (see below).

Podophyllotoxin Binding Assay — The DEAE-filter paper disc assay for colchicine had to be modified to make it suitable for podophyllotoxin. Two DE81 paper discs (Whatman) were washed with cold PMG buffer (4°) by suction, taking care not to dry the paper. Over a period of 1 to 2 min, 100 to 150 μl of the sample were applied and were absorbed to filters. The filters were then rinsed four times with 4 ml of cold PMG buffer by mild suction. The discs were counted in 10 ml of Aquasol (New England Nuclear) or Hydromix (Yorktown) to a counting error of <2%. Identical blanks, lacking only tubulin, amounted to 0.3 to 0.5% of the total radioactivity applied. When 3 or 4 filter papers were used, or when the filters were rinsed with buffer containing 10^-7 M podophyllotoxin, identical results were obtained. Most of the free podophyllotoxin was removed after the first wash. By contrast, the bound complex remained on the paper and was not washed off with up to seven additional washes as shown in Table I. The formation of podophyllotoxin-tubulin complex, detected by the paper disc method described, is a linear function of protein concentration, as shown in Fig. 1.

The filter method was checked against two other methods. In the first, the comparison was with the Sephadex G-100 column method of Weisenberg et al. (11), as shown in Table II. It is clear that the gel filtration and the filter paper methods gave almost identical results; hence for convenience, the latter was used throughout. In the second, a norite/dextran procedure similar to that used by Wilson (10) was used, and a norite method had a high blank (3.5% of total radioactivity), and was not used for this reason.

### Materials

Podophyllotoxin, a kind gift of Dr. Martin Flavin (Laboratory of Biochemistry, National Heart and Lung Institute, National Institutes of Health, Bethesda, Md.), had a specific activity of 3.4 Ci/mmol and was labeled in the 4° position. It was synthesized by methylation of 4'-dimethyl podophyllotoxin with [3H]diazomethane (16, 17). The radiochemical purity of [3H]podophyllotoxin was determined by thin layer chromatography on silica gel plates (Quantum Industries Q1F) in four different solvents: (a) isopropyl ether:ethanol (18:1); Rf = 0.23; (b) chloroform:methyl acetate (4:1); Rf = 0.31; (c) methylene chloride:acetic acid (4:1); Rf = 0.69; (d) ether:methylene chloride (6:1); Rf = 0.24. [3H]Podophyllotoxin was determined on 1-cm sections of the gel scraped into 10 ml of Hydromix (Yorktown). The following purities were found: Solvent a, 85.4%; Solvent b, 88.5%; Solvent c, 91.5%; Solvent d, 88.8%

Tritiated colchicine (ring C, [3H]methoxy), a product of New England Nuclear Corp., had a specific activity of 2.5 Ci/mmol.

Podophyllotoxin was the gift of Dr. W. J. Gensler of Boston University. A Stock solution (1 × 10^-4 M) in ethanol was diluted with PMG buffer such that the ethanol concentration was <0.1%. Concentrations of ethanol up to 1% had no detectable effect on the binding reaction. Concentrations were determined from an extinction coefficient of 4400 at 294 nm (18). Guanosine triphosphate (GTP, Grade IIIS) and 2-(N-morpholino)ethanesulfonic acid were products of Sigma Chemical Co. Tropolone, trimethoxybenzamide and trimethoxybenzamidine were products of Aldrich Chemical Co. and trimethoxyphenylpropionate acid was a product of K & K. Podophyllotoxin methyl ether was synthesized with diazomethane according to published procedures (18, 19). Colchicine analogues were gifts of Dr. Colin Chignell, Vinblastine sulfate was a gift from Eli Lilly and Co. 4'-Demethyl deoxydopophyllotoxin 5,6-glucoside and 4'-carbogencyl 4'-demethyl podophyllotoxin were the kind gifts of Dr. A. von Warburg (Pharmaceutical Division, Sandoz Ltd., Basel, Switzerland).

### Results

**Binding Conditions** — Preliminary experiments had shown that the binding of podophyllotoxin to tubulin was relatively fast and, in the range of concentrations used in most experiments (10^-5 to 10^-7 M podophyllotoxin and 10^-7 M tubulin), at 37° less than 20 min were needed to reach equilibrium. For this reason, samples were generally incubated for 20 to 30 min and then analyzed.

The optimum pH for binding was 6.6 to 6.9 (Fig. 2); Tris/HCl and sodium phosphate buffer of the same pH gave similar results. The pH curve of podophyllotoxin binding does not differ substantially from that of colchicine binding to tubulin (5, 20).

No binding could be detected when podophyllotoxin was incubated with the following proteins: bovine serum albumin, rabbit muscle aldolase, bovine pancreatic ribonuclease, horse liver alcohol dehydrogenase, trypsin, beef liver catalase, beef

### Table I

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<th>Number of washings</th>
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### Table II

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<th>(Bound podophyllotoxin)</th>
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</table>
1136 Podophyllotoxin Binding to Tubulin

FIG. 2. pH dependence of podophyllotoxin and tropolone binding to tubulin. [3H]Podophyllotoxin (3.0 x 10^{-7} M) was incubated with tubulin (1.3 x 10^{-6} M) for 20 min at 37°C in 10 mM MgCl_2 and either 10 mM sodium phosphate buffer (□) or 10 mM Tris/HCl (○). Tropolone (3.3 x 10^{-7} M) was incubated for 20 min with tubulin (2.1 x 10^{-6} M) at 37°C in 10 mM MgCl_2 and 10 mM sodium phosphate buffer (□) or 10 mM Tris/HCl (○). Tropolone binding was evaluated by measuring enhancement of fluorescence.

Liver glutamic dehydrogenase, rabbit muscle lactic dehydrogenase, and bovine thyroglobulin.

No chemical modification of the ligand could be detected upon complex formation. Tubulin was incubated for 30 min with [3H]podophyllotoxin and the complex was separated by the DEAE-filter paper disc method. The podophyllotoxin was then released from tubulin by heating the DEAE-paper at 60°C for 15 min in water. The solution was concentrated and chromatographed on silica gel plates in the four different solvents listed under "Experimental Procedures." In all solvents, more than 97% of the radioactivity moved with authentic podophyllotoxin.

Loss of Binding Activity of Tubulin—At 37°C, the colchicine binding activity of uncomplexed tubulin decays in a first order manner with a t_1/2 of 3 to 5 h, and vinblastine and sucrose protect this binding activity (5, 8, 21-23). In Fig. 3, we compare the effect of preincubation of tubulin at 37°C on the binding capacity of the protein toward colchicine and podophyllotoxin. The decay of the binding capacity for colcemid was also tested. The t_1/2 for podophyllotoxin was 5.0 h, for colchicine it was 4.5 h, and for colcemid it was 5.8 h. When the incubation time is added, these t_1/2 values become, respectively, 5.5 h, 6.0 h, and 6.3 h.

When the preincubation was carried out in the presence of vinblastine or sucrose, the decay of the binding activity for all ligands was much slower (t_1/2 > 14 h in all cases). Vinblastine afforded better protection than sucrose. Heating the protein at temperatures higher than 37°C accelerated the decay of the binding activity, and at 60°C less than 15 min were needed to abolish completely the ability of tubulin to react with podophyllotoxin or colchicine (Table III).

Binding Parameters at Equilibrium—If the overall binding reaction is

\[ T + nP \rightleftharpoons TP_n \]  

where T is tubulin, P is podophyllotoxin, and n is the number of podophyllotoxin binding sites on tubulin, then at equilibrium

\[ r = \frac{nKP}{1 + KP} \]  

where, r is the number of moles of podophyllotoxin bound per mole of tubulin. K is the affinity constant (K = [TP_n] / [P][T]).

Fig. 3. Podophyllotoxin, colchicine, and colcemid binding to tubulin as a function of preincubation time at 37°C. Tubulin (5.6 x 10^{-7} M) was preincubated at 37°C in PMG buffer (O-O), PMG buffer containing 1 M sucrose (△-△), PMG buffer containing 1 x 10^{-4} M vinblastine (VLB) (□-□), all at pH 6.7. After the preincubation period the binding activity of tubulin was measured by incubating an aliquot of the sample with the 3H-labeled ligands at 37°C for 30 min (colcemid and podophyllotoxin), and for 1 h 30 min in the case of colchicine. Colcemid binding was assayed by a method identical to that used for podophyllotoxin.

These results suggested that the lability of colchicine binding resides at least in the trimethoxyphenyl portion of the binding site. They did not, however, shed light on the thermal properties of the tropolone portion of the colchicine site. To investigate this question, we measured the decay in the ability of tubulin to enhance the fluorescence of tropolone. As shown in Table III, heating of tubulin left the tropolone binding capacity of the protein completely intact whereas colchicine and podophyllotoxin binding were completely abolished. An additional difference between the trimethoxyphenyl and tropolone portions of the colchicine binding site is demonstrated in the pH profile shown in Fig. 2. While podophyllotoxin shows a rather sharp optimum near pH 6.7, the fluorescence of tropolone was unaffected over a pH range of 6.5 to 8.8. It seems clear, therefore, that the high lability of the colchicine binding site is restricted to the trimethoxyphenyl portion.
Rearrangement of Equation 2 gives
\[ r/P = nK - Kr, \]
which is the basis of the Scatchard plot shown in Fig. 4. The number of podophyllotoxin binding sites per tubulin dimer was equal to 0.71 (Fig. 4). The \[^{3}H\]podophyllotoxin obtained from the complex was 97% pure whereas the mean radiochemical purity of the starting material was 80% (see "Methods"). Thus the impurities did not appear to bind to tubulin, and the corrected value for the stoichiometry is 0.8 mol of podophyllotoxin per mol of tubulin (110,000 daltons). This is identical to the stoichiometry reported for colchicine (3, 6, 7).

The affinity constant at 37° was 1.6 to 1.8 \(\times\) 10\(^{6}\) M\(^{-1}\) (\(K_d = 1/K = 5.5\) to 5.2 \(\times\) 10\(^{-7}\) M). This should be compared with a \(K_d\) value of 7 \(\times\) 10\(^{-7}\) M obtained for pig brain tubulin (9), and a concentration of 5 \(\times\) 10\(^{-7}\) M required for half-maximal inhibition of axonal transport (24). At lower temperatures, the constant was lower (Fig. 4). A van't Hoff plot of log \(K\) versus the reciprocal of the absolute temperature was linear in the region 22-37° (inset Fig. 4) and yielded an estimate of 4.8 kcal/mol for the standard enthalpy of binding (\(\Delta H^0\)).

The standard free energy (\(\Delta G^0\)) of binding at 37° was equal to -8.8 kcal/mol and \(\Delta S^0 = 43\) cal deg\(^{-1}\) mol\(^{-1}\). The entropy value should be compared with 62 cal deg\(^{-1}\) mol\(^{-1}\) obtained from equilibrium binding of colchicine (7).

**Association Rate Constant and Activation Energy** - If podophyllotoxin binding is assumed to be bimolecular, the association rate constant (\(k_1\)) is
\[ k_1 = \frac{d[P][T]}{dt} \]
where \((d[P][T])/dt\) is the rate of formation of the complex and \([P]\) and \([T]\) are the concentrations of free podophyllotoxin and unoccupied tubulin. Conditions were adjusted such that <10% of the reactants were consumed during the intervals when the curves were linear and we have thus assumed that \(P = P_0\) and \(T = T_0\), where \(P_0\) and \(T_0\) are the initial concentrations.

When the protein concentration was 190 nM, the rate curves were linear for the first 2 to 3 min of incubation over a concentration of 58 to 188 nM podophyllotoxin (Fig. 5). Similarly, when podophyllotoxin was held constant at 138 nM.

![TABLE III](https://www.jbc.org/)

**Table III**

*Temperature effect on colchicine, podophyllotoxin, and tropolone binding activity of tubulin*

Tubulin (1.5 \(\times\) 10\(^{-4}\) M) was preincubated in PMG buffer, pH 6.7, at the temperature and for the time indicated. Then 200 \(\mu\)l of this sample were added to 50 \(\mu\)l of solution containing 5.8 \(\times\) 10\(^{-7}\) M \[^{3}H\]podophyllotoxin, 1.2 \(\times\) 10\(^{-8}\) M colchicine, or 10\(^{-5}\) M tropolone, and were incubated for 30 min at 37°. Podophyllotoxin binding was measured by the disc method, whereas colchicine and tropolone binding were measured by fluorescence (7). The results are expressed as the percentage of the binding detected in samples when the protein was not preincubated.

<table>
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<th>Temperature</th>
<th>Time (Min)</th>
<th>Percentage of initial binding activity</th>
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<tbody>
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<td>37°</td>
<td>1</td>
<td>82% colchicine 86% podophyllotoxin 98% tropolone</td>
</tr>
<tr>
<td>45°</td>
<td>1</td>
<td>60% colchicine 46% podophyllotoxin 97% tropolone</td>
</tr>
<tr>
<td>60°</td>
<td>0.5</td>
<td>0% colchicine 0% podophyllotoxin 98% tropolone</td>
</tr>
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</table>

![FIG. 4](https://www.jbc.org/)

Fig. 4. The temperature dependence of podophyllotoxin binding to tubulin. The reaction mixture contained 5.8 \(\times\) 10\(^{-7}\) M tubulin in PMG buffer, pH 6.7. Tubes were incubated for 20 min at 37° (filled circles), 40 min at 28° (open circles), and 60 min at 22° (open triangles). Results are expressed by a Scatchard plot (\(r = \) moles of podophyllotoxin bound per mole of tubulin (110,000 daltons), \(P = \) free podophyllotoxin concentration). The inset shows log \(K\) against 10\(^{1/T}\).*

![FIG. 5](https://www.jbc.org/)

Fig. 5. The rate of podophyllotoxin binding as a function of the concentrations of podophyllotoxin and tubulin. All incubations were at 37° in PMG buffer. *Upper panel*, podophyllotoxin was constant at 138 nM. Numbers refer to nM tubulin concentrations. *Lower panel*, tubulin was held constant at 190 nM. Numbers refer to nM podophyllotoxin concentrations. The dashed lines are continuations of the slopes for the initial rates.
concentration, binding curves remained linear for 3 to 10 min over tubulin concentrations ranging from 95 to 285 nM. The second order rate constants ($k_2$) calculated from these data are listed in Table IV; the mean of these values is $3.8 \times 10^6$ M$^{-1}$ h$^{-1}$. These results suggest that podophyllotoxin binding is truly second order under the conditions tested.

Since the association rate constant determined for podophyllotoxin is 10 times higher than that for colchicine (0.36 $\times 10^6$ M$^{-1}$ h$^{-1}$ (21), 0.41 $\times 10^6$ M$^{-1}$ h$^{-1}$ (25), or 0.12 to 0.48 $\times 10^6$ M$^{-1}$ h$^{-1}$ (26)), it was important to measure the activation energies ($E_a$) for both reactions. A comparison of the temperature effect on colchicine and podophyllotoxin binding, and the Arrhenius plots derived therefrom, is presented in Fig. 6. The activation energy for podophyllotoxin is 14.7 kcal/mol, that for colchicine 20.3 kcal/mol. The higher activation energy for podophyllotoxin binding on the assumption that only the trime-thoxyphenyl moiety of this compound was recognized by the colchicine binding site, as shown by enhancement of fluorescence or blocking of colchicine binding (7), neither has any effect on podophyllotoxin binding (3, 8, 25, 28), these reactions were carried out at a time when >90% equilibrium had been attained. Furthermore, since podophyllotoxin binding is more rapid than colchicine binding, failure of equilibration would have opposing effects on $K_i$ and $K_d$ depending on which ligand is labeled. One possible explanation, that the two ligands might interact, seems unlikely since no difference spectra could be elicited between combined and separate solutions of podophyllotoxin and colchicine, and since the mobility of $1 \times 10^{-6}$ M labeled podophyllotoxin on Sephadex G-10 (in PMG buffer) was not altered by $1 \times 10^{-5}$ M colchicine. It is possible that the discrepancy between the two constants results from the partial overlap of the binding sites.

Surprisingly, manipulations of the tropolone ring, as shown in isocolchicine, produced analogues that were not able to block podophyllotoxin binding. On the other hand, although both tropolone and methyltropolone bind to the site, as shown by enhancement of fluorescence or blocking of colchicine binding (7), neither has any effect on podophyllotoxin binding. This suggests that the remainder of the podophyllotoxin molecule need not overlap the tropolone domain of the colchicine binding site when the trimethoxyphenyl moiety is binding. This is also shown by the finding that podophyllotoxin did not affect the fluorescence enhancement of tropolone resulting from its binding to tubulin.

Dissociation Rate Constant ($k_{-1}$) — In view of the discrepancy between the affinity constant ($K$) determined in equilibrium experiments and the ratio of the association ($k_2$) and dissociation ($k_{-1}$) rate constants for colchicine (21, 25, 26), it was of interest to determine the $k_2/k_{-1}$ ratio for podophyllotoxin binding. In order to determine the dissociation of the podophyllotoxin-tubulin complex, the bound podophyllotoxin was separated from the free by passing the sample at 4° through a Sephadex G-75 column (24 $\times$ 1.4 cm). The podophyllotoxin-tubulin complex was diluted ~60 times so that reassociation was negligible, and was then incubated at 37° in PMG buffer. As shown in Fig. 7, the $t_{1/2}$ of dissociation of the complex was ~22 min, giving $k_{-1} = 1.9$ h$^{-1}$. The ratio of the rate constant yields an association constant of $2.1 \times 10^6$ M$^{-1}$, which is in good agreement with the value obtained by equilibrium methods.2

Analogues — Numerous colchicine analogues have been found to block [3H]colchicine binding to tubulin (2, 7, 8). In most cases it has not been established whether these compete for the A ring or C ring regions or both, or whether binding at one locus necessarily implied occupancy of the whole site. We therefore tested certain analogues for their effect on podophyllotoxin binding on the assumption that only the trimethoxyphenyl moiety of this compound was recognized by the colchicine binding site. If the trimethoxyphenyl ring is a site of interaction of both colchicine and podophyllotoxin with tubulin, it would be expected that analogues with bulky substituents in the trimethoxyphenyl ring are unable to bind to tubulin. This is indeed the case: colchicoside, in which one carbobenzoxy-4'-demethyl podophyllotoxin, which possesses bulky substituents in the 4' position of the podophyllotoxin molecule, are totally ineffective in inhibiting colchicine or podophyllotoxin binding (Table V). These analogues also supply evidence that podophyllotoxin binds to tubulin through its trimethoxyphenyl portion. Simple trimethoxyphenyl derivatives do not appear to interact with the colchicine binding site (Table V). However, it has recently been shown that mescaline (3,4,5-trimethoxyphenethylamine) is an antimitotic agent (27).

Since podophyllotoxin is known to inhibit colchicine binding competitively, it was expected that colchicine would similarly block podophyllotoxin binding comparatively. Rearrangement of Equation 2 yields

$$\frac{1}{r} = \frac{1}{n} - \frac{1}{nK_i}$$

(5)

In the presence of an inhibitor, $I$, Equation 5 becomes

$$\frac{1}{r} = \frac{1}{n} - \frac{1}{nK_i} + \frac{1}{nK_i}$$

(6)

where $K_i = \frac{[T][I]}{[IT]}$. As shown in Fig. 8, colchicine was a competitive inhibitor of podophyllotoxin binding. The $K_i$ was $2.1 \times 10^{-6}$ M. An important problem for which we have been unable to supply an answer is the discrepancy in ligand affinities for tubulin when these are measured as the $K_i$ or $K_d$ under identical conditions. The $K_i$ values for podophyllotoxin and colchicine are $2.0 \times 10^{-6}$ M and $2.1 \times 10^{-6}$ M, respectively (7). These differences have been consistently observed. It is conceivable that these discrepancies result from incomplete equilibration. However, as shown by others as well as by us (3, 8, 25, 28), these reactions were carried out at a time when >90% equilibrium had been attained. Furthermore, since podophyllotoxin binding is more rapid than colchicine binding, failure of equilibration would have opposing effects on $K_i$ and $K_d$ depending on which ligand is labeled. One possible explanation, that the two ligands might interact, seems unlikely since no difference spectra could be elicited between combined and separate solutions of podophyllotoxin and colchicine, and since the mobility of $1 \times 10^{-6}$ M labeled podophyllotoxin on Sephadex G-10 (in PMG buffer) was not altered by $1 \times 10^{-5}$ M colchicine. It is possible that the discrepancy between the two constants results from the partial overlap of the binding sites.

1 For colchicine, the apparent dissociation is the sum of decay of the site plus true dissociation (29). Since $t_{1/2}$ for the podophyllotoxin-tubulin complex dissociation is 22 min and decay of unoccupied site is about 300 min, the decay factor does not play a significant role in podophyllotoxin dissociation.

### Table IV

<table>
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<tr>
<th>[Podophyllotoxin]</th>
<th>[Tubulin]</th>
<th>d[PT]/dt</th>
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<td>150 h-'</td>
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1 For colchicine, the apparent dissociation is the sum of decay of the site plus true dissociation (29). Since $t_{1/2}$ for the podophyllotoxin-tubulin complex dissociation is 22 min and decay of unoccupied site is about 300 min, the decay factor does not play a significant role in podophyllotoxin dissociation.
Podophyllotoxin Binding to Tubulin

Fig. 6. Temperature dependence of podophyllotoxin and colchicine association rates. All reactions were carried out in PMG buffer. Left panel, 82 nM podophyllotoxin was incubated with 1.62 μM tubulin in PMG buffer. The inset depicts the rates plotted as (d[PT]/dt versus 10^(-T)), where (d[PT]/dt) is the rate of formation of the podophyllotoxin-tubulin complex expressed as nmol liter^-1 h^-1. Right panel, 84 nM colchicine was incubated with 2.14 μM tubulin in PMG buffer. The inset shows a plot of (d[CT]/dt versus 10^(-T)), where (d[CT]/dt) is the rate of formation of the colchicine-tubulin complex expressed as nmol liter^-1 h^-1.

Table V

Comparison of the effect of colchicine analogues on podophyllotoxin and colchicine binding to tubulin

<table>
<thead>
<tr>
<th>Compound</th>
<th>Colchicine substitutions</th>
<th>Inhibition of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R₃</td>
<td>R₂</td>
</tr>
<tr>
<td>Colchicine</td>
<td>OCH₃</td>
<td>OCH₃</td>
</tr>
<tr>
<td>Colcemid</td>
<td>OCH₃</td>
<td>OCH₃</td>
</tr>
<tr>
<td>Iasocolchicine</td>
<td>OCH₃</td>
<td>-₉</td>
</tr>
<tr>
<td>Colchioside</td>
<td>CH₃-OH</td>
<td>OCH₃</td>
</tr>
<tr>
<td>Podophyllotoxin</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trimethoxybenzilcine</td>
<td></td>
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</tr>
<tr>
<td>Trimethoxybenzaline</td>
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<tr>
<td>Trimethoxyphenylalanic Acid</td>
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<td>4'-Carboxy-4-demethyl-</td>
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<td>4'-Demethyl desoxy-</td>
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<tr>
<td>Methyltropolone</td>
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</tbody>
</table>

*a* In isocolchicine ring C, the oxygen and R₃ group (OCH₃) are inverted with respect to colchicine.

Fig. 7. Dissociation of the tubulin-podophyllotoxin complex. Tubulin (1.3 × 10^-3 M) was incubated with [3H]podophyllotoxin (7.3 × 10^-7 M) for 30 min at 37°C and the bound podophyllotoxin was separated from the free by passing the sample through a Sephadex G-75 column (24 × 1.4 cm) equilibrated with PMG buffer at 4°C. The podophyllotoxin-tubulin complex, eluted in the void volume, was diluted ~60 times with PMG buffer containing 0.2% albumin and then incubated at 37°C.

**DISCUSSION**

A competitive inhibitor is usually considered to be a compound that prevents "substrate" binding by an interaction at the same site. However, competitive kinetics are also possible by mutual distortion of the respective binding sites or by steric hindrance from adjacent sites (29). These variations are not easily distinguished from one another. It was, therefore, important to characterize the podophyllotoxin effect since only a small portion of its structure resembles colchicine. The following properties of the two binding processes were found to be very similar or identical. (a) A pH optimum at 6.7. The narrow range of pH optimum reflects the ionization of the protein since neither colchicine or podophyllotoxin possess ionizable groups. (b) Stoichiometry approaching 1 mol of ligand per 110,000 molecular weight. The observed value for podophyllotoxin, corrected for impurities, was ~0.8 with a podophyllotoxin:colchicine ratio of ~1.0. (c) Lability. The site decays with a half-life of 4 to 6 h for both ligands. Vinblastine or 1 M sucrose stabilize the binding of both ligands identically. (d) Similar thermodynamic parameters at equilibrium. Both reactions are entropy-driven: 62 cal deg^-1 mol^-1 for colchicine and 43 cal deg^-1 mol^-1 for podophyllotoxin. (e) Mutual competitive inhibition. Thus colchicine blocks podophyllotoxin binding and podophyllotoxin blocks colchicine binding.

The above arguments suggest that these two ligands share at least a part of the same binding site on tubulin. Nevertheless, certain differences in the binding processes for these
Podophyllotoxin Binding to Tubulin

![Graph](image)

**FIG. 8.** Double reciprocal plot of colchicine inhibition of podophyllotoxin binding. The concentrations of colchicine used were 5.0 μM (Δ—Δ), 5.0 μM (○—○), 7.5 μM (□—□). Open circles (□—□) no colchicine. The tubulin concentration was 1.9 μM, temperature = 37°C, incubation time = 1.5 h; r is the number of moles of podophyllotoxin bound per mole of tubulin.

Podophyllotoxin binds relatively slowly when compared with ANS, which interacts "instantaneously" with tubulin and at a different site (30, 31). However, podophyllotoxin is a faster reactant than colchicine, and at 37°C, its forward rate constant (kₐ) is 10 times higher than that for colchicine. This appears to be mainly due to the difference in the activation energy which is 20.3 kcal/mol for colchicine and 14.7 kcal/mol for podophyllotoxin. The structural reason for this difference is, at present, unknown.

Tropolone inhibits colchicine binding competitively (7), but has no effect on podophyllotoxin. Conversely, podophyllotoxin does not affect tropolone binding. The results strongly suggest that the trimethoxyphenyl portion of the colchicine domain is shared by colchicine and podophyllotoxin, whereas the tropolone portion of the site recognizes only colchicine and not podophyllotoxin. Interestingly enough, the tropolone site does not show the pH and temperature dependence exhibited by podophyllotoxin or colchicine, thus suggesting that these properties are referable to the trimethoxyphenyl binding region. That the trimethoxyphenyl ring is a point of attachment of both colchicine and podophyllotoxin is shown by the observation that analogues with a bulky substituent instead of one of these in common, that portion of the site where the trimethoxyphenyl ring interacts.

We may conclude, therefore, that colchicine and podophyllotoxin each bind at least at two tubulin domains and have one of these in common, that portion of the site where the trimethoxyphenyl ring interacts.

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