Metabolites of All-trans-retinoic Acid in Bile: Identification of All-trans- and 13-cis-retinoyl Glucuronides

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The metabolites of all-trans-[1H]retinoic acid were studied in the rat bile. In the bile duct cannulated rat 80 to 86% of the dose is excreted into the bile within 24 h after the intravenous administration of either a physiological or pharmacological dose of all-trans-[1H]retinoic acid. Polar metabolites of retinoid acid predominate (73 to 96% of bile 3H) in the bile at all times; some free retinoic acid (0.2 to 4.8% of bile 3H) is excreted into the bile during the initial 6-h period after dosing. Retinoyl glucuronides are excreted into the bile for 12 h after dosing; their excretion is highest during the first 2 h. More retinoyl glucuronide is excreted than from the physiological dose (10% of the radiolabel dose) than from the physiological dose (4.4% of the dose) of all-trans-retinoic acid. The retinoyl glucuronides were separated and were shown to consist of all-trans- and 13-cis-retinoyl glucuronides in a ratio of 1.0 to 1.0. Since the starting material was 99% all-trans-retinoic acid and the methods used do not cause isomerization, it is concluded that cis-trans isomerization of retinoid acid is a physiologically relevant reaction.

Studies on the metabolism of retinoid acid are of considerable importance because of the possibility that this physiologically occurring retinoid may be the active form of vitamin A, and because it has therapeutic potential in the carcinogenesis process (1, 2). Recent studies suggest that the rapid disappearance of administered retinoic acid (3–6) is associated with the appearance of many metabolites in the plasma and bile of rats (7, 8). One of the identified biliary metabolites of retinoid acid is retinoyl glucuronide (7, 9); it accounts for 12% of biliary metabolites of retinoic acid after a pharmacological dose (7). These studies have also suggested that the retinoyl glucuronide present in bile is a mixture of all-trans and 13-cis isomers.

The present report demonstrates that 13-cis- and all-trans-retinoyl glucuronides are in vivo metabolites of all-trans-retinoic acid and are found in the bile after a physiological as well as after a pharmacological dose of all-trans-retinoic acid.

EXPERIMENTAL PROCEDURES

Radiochemicals, Their Purification and Preparation of Doses—

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All-trans-[11,12-3H]retinoic acid, specific activity 31 Ci/mmol (a gift from Hoffmann-La Roche, Inc., Nutley, NJ) and all-trans-[10-3H]retinoic acid, specific activity 1.33 Ci/mmol (a gift from the National Cancer Institute) were examined by high performance liquid chromatography prior to use, using a Zorbax-ODS analytical column (0.46 cm inside diameter × 25 cm; DuPont Analytical Instruments, Wilmington, DE) that was developed with methanol:water (86:32, v/v) containing 0.01 M ammonium acetate and that resolves all-trans-retinoic acid from its isomers and other impurities. Depending on the impurities present in the radiolabeled samples, the compounds were purified as follows. If there were no isomers of retinoic acid present, the material was purified on a Lipidex 5000 (Packard Instruments, Inc., Downers Grove, IL) column that was developed with methanol:water (86:32, v/v) containing 0.01 M ammonium acetate, immediately prior to use. This chromatographic procedure separates all-trans-retinoic acid from 5,6-epoxyretinoic acid and other polar and less polar impurities but does not resolve retinoic acid isomers. If the radioactive sample contained retinoic acid isomers, it was purified immediately prior to use by HPLC on an analytical reverse-phase Bondapak X-C18 column (0.4 cm inside diameter × 30 cm; Waters Associates, Milford, MA) that was developed with methanol:water (86:32, v/v) containing 0.01 M ammonium acetate and that separates all-trans-retinoic acid from its isomers and other impurities. Unlabeled all-trans-retinoic acid (Eastman Organic Chemicals, Rochester, NY) did not require purification.

For the studies dealing with the isolation and identification of 13-cis-retinoyl glucuronide the rats were dosed with purified all-trans-[10-3H]retinoic acid that was mixed with unlabeled all-trans-retinoic acid to a specific activity of 55 × 10^6 dpm/µg and 2.22 mg of this dose injected into stock rats as described (9). For the studies involving a comparison of biliary metabolites of retinoic acid using physiological and pharmacological levels of retinoic acid, the doses were prepared as follows: purified all-trans-[11,12-3H]retinoic acid was mixed with unlabeled all-trans-retinoic acid to a specific activity of 55 × 10^6 dpm/µg and 2.22 mg of this dose injected into stock rats as described (9). Vitamin A-deficient rats were injected intragastrically with 12.7 µg of purified all-trans-[10-3H]retinoic acid, specific activity 7.09 × 10^6 dpm/µg, dissolved in 0.1 ml of dimethylsulfoxide.

Chemicals and Solvents—All chemicals and solvents were of reagent grade or of HPLC grade.

TWEEN 40 (polyoxyethylene sorbitan monopalmitate), butylated hydroxytoluene, n-propyl gallate, bovine albumin, and β-d-glucuronidase (from bovine liver, Type B-19, dimethylsulfoxide, and ethylenediaminetetraacetic acid were purchased from Sigma.

All-trans-5,6-epoxyretinoic acid and 13-cis-retinoic acid (gifts from the National Cancer Institute) were purified on an analytical reverse phase Zorbax-ODS column using a solvent system identical with that described for Fig. 3. The purified HPLC standards were stored under nitrogen at ~70°C.

Preparation of Animals and Bile Duct Cannulation—Vitamin A-deficient rats were prepared as described previously (10) and used in the experiments when they had reached a weight plateau (at about 8 weeks of age). Male stock rats, about 8 weeks old, were obtained from the Holtzman Co. (Madison, WI) shortly before use.

Rats were lightly anesthetized with ether and injected intragastrically with phenobarbital (25 mg/kg of body weight). The bile duct was then cannulated with polyethylene tubing. After bile flow was

$The abbreviations used are: HPLC, high performance liquid chromatography; BHT, butylated hydroxytoluene; BDTA, ethylenediaminetetraacetic acid.
established, the stock rats were injected intraperitoneally with all-trans-retinoic acid, and then their abdominal incision closed with sutures and surgical clips, leaving the bile duct cannula exposed to the outside. The surgical procedure was similar for the vitamin A-deficient rats, except that the dose was injected intragastrically. The rats were then placed in restraining cages and allowed 10% dextrose solution ad libitum during the period of bile collection (24 h). The rats were housed in a room equipped with amber lights. The bile was collected under $N_2$ over ice in glass vials that contained $100 \mu g$ each of n-propyl gallate and butylated hydroxytoluene. At each collection time, aliquots of bile were removed for determination of radioactivity and the collected bile stored under $-20^\circ C$ until further analysis.

**Extraction of Bile; Chromatography of Extracts**—Bile was extracted with 1-butanol as described (9) except that n-propyl gallate, and EDTA ($100 \mu g/ml$) were added to the aqueous phase, butanol contained BHT ($50 \mu g/ml$), and the extraction was done under $N_2$. The final butanol extract was evaporated under reduced pressure and the metabolites redissolved in methanol for chromatography.

Sephadex LH-20 (particle size 25 to 100 $\mu m$, Pharmacia Fine Chemical, Inc., Piscataway, NJ) was equilibrated with chloroform-hexanemethanol ($65:35:6, v/v/v$) and then packed into a glass column ($2 \times 55$ cm). The bile extract was applied onto the column in a small volume of methanol chloroform ($1:1, v/v$), and the column developed with the above solvent until 80 ml had been collected; thereafter, the elution was continued with acetone:methanol ($1:1, v/v$). All solvents contained BHT ($50 \mu g/ml$).

Anion exchange chromatography was carried out on a DEAE-cellulose (Whatman Cellex-D column ($2.5 cm$ inside diameter $\times 30$ cm, packed to a height of 4 cm) that had been converted to anion form. The samples were applied in a small volume of ethanol and the column was first developed with ethanol, followed by acidified (0.3% HCl) ethanol.

For the analysis of fresh bile, 20- to 50-$\mu l$ aliquots of bile were deproteinized with 5 volumes of cold ethanol, the precipitate removed by centrifugation, and the supernatant evaporated to a small volume and applied directly onto HPLC columns.

HPLC was done on a Beckman Model 332 Gradient Liquid Chromatograph (Beckman Instruments, Inc., Lincolnwood, IL) that was equipped with Waters Associates Model 440 Absorbance Detector fixed at 240 nm and a Waters Associates Model U6K Universal Injector. The analytical columns used were Bondapak $C_18$ (Waters Associates; $0.4 cm$ inside diameter $\times 30$ cm) and Zorbax-ODS (DuPont Instruments, $0.46 cm$ inside diameter $\times 25$ cm). The semipreparative column was a Partisil M9 10 ODS-2 (0.94 cm inside diameter $\times 25$ cm, Whatman). Chromatography was done at ambient temperatures in a room equipped with amber lighting. The flow rate was 2 ml/min for the analytical columns and 4 ml/min for the semipreparative column.

**Other Procedures**—Incubation with $\beta$-glucuronidase was essentially as described previously (7) except that after incubation the mixture was deproteinized with ethanol as described for fresh bile above.

All operations described here were carried out under amber light; samples were collected on ice, protected from oxidation, and stored at $-70^\circ C$. Radioactivity was determined in a Packard Tri-Carb Model 3255 scintillation counter equipped with an automatic external standardization system. Samples for counting were dissolved in $3a70B$ mixture was deproteinized with ethanol as described for fresh bile.

**RESULTS**

Isolation and Identification of 13-cis-Retinoyl Glucuronides—Bile collected from cannulated stock rats 6 h after an intraperitoneal injection of 3.1 mg of all-trans-[10-3H]retinoic acid (specific activity $59 \times 10^5$ dpm/$\mu g$) was extracted and chromatographed on Sephadex LH-20 (Fig. 1A) as described under “Experimental Procedures.” This chromatographic procedure results in a partial purification of the biliary metabolites of retinoic acid. Fractions 15 to 28, 105 to 130, and 140 to 180 contained a yellow-green material. A small amount of radioactivity eluted with all-trans-retinoic acid standard (fraction 40), a fraction that also contains 5,6-epoxyretinoic acids. Most of the radioactivity (86 to 97%) eluted as a single peak in fractions 110 to 130. These fractions were pooled, the solvent evaporated under water pump vacuum and applied to a Partisil M9 PXS 10/25 Whatman semi-preparative HPLC reverse-phase column (Whatman Partisil M9, 10/25). The elution was isocratic with a mixture of methanol:water (70:30, v/v), containing 0.01 M ammonium acetate, and a flow rate of 4 ml/min for the semipreparative column (Whatman Partisil M9, 10/25).

In a previous paper (7), we reported the isolation and characterization of a mixture of all-trans- and 13-cis-retinyl glucuronides from rat bile. The mass spectrum of these glucuronides is shown in Fig. 2; it does not distinguish between the isomers.

The individual retinyl glucuronides (peak E, 13-cis-retinoyl glucuronide, and peak G, all-trans-retinoyl glucuronide) were collected from the reverse-phase semipreparative col-

![Fig. 1. Chromatography of biliary metabolites of all-trans-retinoic acid. Butanol extracts of bile were first chromatographed on a Sephadex LH-20 column using a solvent mixture consisting of chloroform-hexanemethanol (65:35:6, v/v/v) containing 50 $\mu g$ of BHT/ml. A solvent mixture consisting of acetone:methanol (1:1, v/v) containing 50 $\mu g$ of BHT/ml was started at 80 ml (arrow, A). The major radioactive peak from the column in A was pooled, evaporated to a small volume, and aliquots of it chromatographed on an HPLC reverse-phase semi-preparative column (Whatman Partisil M9, 10/25). The elution isocratic with a mixture of methanol:water (70:30, v/v), containing 0.01 M ammonium acetate, and a flow rate of 4 ml/min for the semipreparative column (Whatman Partisil M9, 10/25).

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The individual retinyl glucuronides (peak E, 13-cis-retinoyl glucuronide, and peak G, all-trans-retinoyl glucuronide) were collected from the reverse-phase semipreparative col-
Retention of retinoid glucuronides was found migrating with polar and nonpolar metabolites, with a small amount as free retinoic acid.

Recovery Studies—In our studies on the metabolism of retinoic acid, great care was exercised to prevent degradation of the isolated metabolites during the isolation procedure and storage. Regardless of the care and precautions taken, a small decomposition and isomerization of vitamin A compounds always occurred. To determine the extent of such degradation, control experiments are carried out with known standards.
Retinoyl Glucuronides in Bile

Fig. 5. Structures of retinoyl glucuronides: all-trans-retinoyl glucuronide, A; 13-cis-retinoyl glucuronide, B.

Fig. 6. Incubation of 13-cis-retinoyl glucuronide with β-D-glucuronidase. Peak E was separated from peak G as described in Fig. 3 and incubated with boiled or fresh β-D-glucuronidase. Extracts from incubation mixtures were chromatographed on a Zorbax-ODS analytical column by isocratic elution with methanol:water (68:32, v/v) containing 0.01 M ammonium acetate, with a flow rate of 1.5 ml/min. A, peak E after the incubation with boiled enzyme; B, peak E after the incubation with fresh enzyme. Arrows indicate the elution positions of UV standards: all-trans-5,6-epoxyretinoic acid (1), 13-cis-retinoic acid (2); all-trans-retinoic acid (3).

Although there is no guarantee that an unknown metabolite will behave like the standard during a recovery test, a control experiment is necessary to evaluate the feasibility of the various isolation procedures to be employed.

When labeled all-trans-retinoic acid was added to the bile collected from untreated rats and the bile processed as described under "Experimental Procedures," the overall recovery of radioactivity was 86%. Of this radioactivity, 77% was all-trans-retinoic acid, 11% was 13-cis-retinoic acid, 0.8% was 5,6-epoxyretinoic acid, while the remaining radioactivity was distributed among various polar and nonpolar compounds.

In most of our studies that deal with specific metabolites and the quantitation of these metabolites, we routinely apply fresh, deproteinized bile directly onto HPLC columns, as this procedure reduces the isolation steps to a minimum and yields very reproducible HPLC profiles. When using this procedure to evaluate the recovery of purified, labeled all-trans-retinoic acid added to fresh bile from nondosed rats, 94% of the radioactivity was recovered as all-trans-retinoic acid; 0.1% of the radioactivity co-migrated with 13-cis-retinoic acid, 2% with 5,6-epoxyretinoic acid, while 1% and 3% of the radioactivity, respectively, was associated with the very polar and nonpolar eluates. The chromatography of all-trans-retinoic acid injected directly onto the HPLC column did not cause any isomerization or decomposition.

Since the lengthy butanol extraction procedure is associated with some isomerization and decomposition of all-trans-retinoic acid, we used this method only for the generation of specific metabolites; while for the quantitation of the various biliary metabolites of retinoic acid, we examined fresh bile directly.

Comparison of Biliary Metabolites Produced from Pharmacological or Physiological Doses of [3H]Retinoic Acid—The bile ducts of stock rats were cannulated, the animals injected intraperitoneally with 2.22 mg of all-trans-[11,12-3H]retinoic acid, specific activity 56 × 10^3 dpm/μg and the bile collected as described under "Experimental Procedures."

In a parallel experiment, the bile ducts of vitamin A-deficient rats were cannulated and the rats injected intrajeugularly with 12.7 μg of all-trans-[10-3H]retinoic acid, specific activity 7.1 × 10^6 dpm/μg. The bile was collected at 2-h intervals, aliquots removed for determination of radioactivity, and the remaining bile stored at −20 °C for further chromatography.

Fig. 7 illustrates that the excretion pattern of radioactivity in bile is very similar for both of the retinoic acid dose levels used. The maximum excretion of radiolabel occurs between 2 to 4 h after the administration of all-trans-retinoic acid and had decreased considerably by 8 h. At 6 h, 60 to 70% of the dosed radioactivity had already appeared in the bile, and at
24 h, the bile contained 80 to 85% of dose radioactivity. Tables I and II show the distribution of the bile radioactivity in the various chromatographic fractions. It is evident that polar metabolites of retinoic acid predominate in the bile at all times, although some free retinoic acid is excreted during the first 4 h after dosing (Tables I and II).

An example of an incubation of fresh bile with β-D-glucuronidase is shown in Fig. 8. The upper panel (A) represents the biliary metabolite profile obtained after an incubation of fresh bile with boiled β-D-glucuronidase. The bile for this experiment was an aliquot from the first 2-h collection period after the injection of all-trans-retinoic acid, and it contains some free 13-cis- and all-trans-retinoic acids. At this time, there is a considerable amount of radioactivity (about 14% of column \(^{3}H\)) in the area of retinoyl glucuronides (peaks E and G). After an incubation with fresh β-D-glucuronidase (Fig. 8, lower panel, B), 80% of the radioactivity that had previously been associated with the retinoyl glucuronides was hydrolyzed. This resulted in a corresponding increase in radioactivity in the elution areas of 13-cis- and all-trans-retinoic acid.

In subsequent studies, the biliary retinoyl glucuronides were resolved using an HPLC system similar to that described in Fig. 3; thereafter, they were individually quantitated.

The rate of excretion of retinoyl glucuronides is illustrated in Fig. 9. A relatively larger amount of retinoyl glucuronide is excreted from the pharmacological dose during each time period as compared to the amount excreted after a physiological dose of retinoic acid. At 24 h after the dose, about 10% of dose radiolabel is excreted in the bile in the form of retinoyl glucuronides from the 2.22-mg dose, while only 4.4% of the radiolabel from the 12.7-μg dose of retinoic acid is in the form of retinoyl glucuronides. Retinoyl glucuronide excretion is maximum during the first 2 h after dosing, when 21% of dose radioactivity is in the retinoyl glucuronide fraction at the 2.22-mg dose level and 13.9% at the physiological dose level (Tables I and II).

Table III presents the biliary excretion of retinoyl glucuronides as a function of time after dose and as a function of bile flow. With the pharmacological dose of all-trans-retinoic acid (which was 220 times that of the physiological dose), this 200:1 relationship holds also for the amount of retinoyl glucuronides excreted during the first 6 h, when expressed as a function of

### Table I

**Distribution of bile radioactivity in the various chromatographic fractions after the injection of a pharmacological dose of all-trans-[\(^{3}H\)]retinoic acid**

<table>
<thead>
<tr>
<th>Fractions</th>
<th>Time period after dosing during which bile was collected</th>
<th>% total bile (^{3}H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar metabolites (^a)</td>
<td>0-2 h</td>
<td>73.3</td>
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<tr>
<td>Retinoyl glucuronides (^a)</td>
<td>2-4 h</td>
<td>77.2</td>
</tr>
<tr>
<td>Retinoic acids (^a)</td>
<td>4-6 h</td>
<td>94.0</td>
</tr>
<tr>
<td>Methanol-eluted fraction (^a)</td>
<td>6-12 h</td>
<td>92.5</td>
</tr>
<tr>
<td></td>
<td>12-24 h</td>
<td>93.0</td>
</tr>
</tbody>
</table>

\(^a\) Deproteinized aliquots of bile were chromatographed on the HPLC system described in Fig. 3. The fractions were collected and their radioactivity determined. Each value represents the averages of bile assays from two rats.

### Table II

**Distribution of bile radioactivity in the various chromatographic fractions after the injection of a physiological dose of all-trans-[\(^{3}H\)]retinoic acid**

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Time period after dosing during which bile was collected</th>
<th>% total bile (^{3}H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar metabolites (^a)</td>
<td>0-2 h</td>
<td>76.1</td>
</tr>
<tr>
<td>Retinoyl glucuronides (^a)</td>
<td>2-4 h</td>
<td>88.6</td>
</tr>
<tr>
<td>Retinoic acids (^a)</td>
<td>4-6 h</td>
<td>96.2</td>
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<tr>
<td>Methanol-eluted fraction (^a)</td>
<td>6-8 h</td>
<td>96.5</td>
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<td></td>
<td>8-10 h</td>
<td>91.0</td>
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<tr>
<td></td>
<td>10-12 h</td>
<td>92.1</td>
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<tr>
<td></td>
<td>12-16 h</td>
<td>96.1</td>
</tr>
<tr>
<td></td>
<td>16-20 h</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>20-24 h</td>
<td>100</td>
</tr>
</tbody>
</table>

\(^a\) Deproteinized aliquots of bile were chromatographed as described in Fig. 3, the fractions collected and their radioactivity determined. Each value is the average from assays of bile samples from two to six rats.

### Table III

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Time period after dosing during which bile was collected</th>
<th>% total bile (^{3}H)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polar metabolites (^a)</td>
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<td></td>
<td>20-24 h</td>
<td>100</td>
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</table>

\(^a\) Deproteinized aliquots of bile were chromatographed on the HPLC system described in Fig. 3. The fractions collected and their radioactivity determined. Each value is the average from assays of bile samples from two to six rats.

\(^a\) Combined all-trans and 13-cis isomers.

\(^a\) Pooled fractions 120 to 140, as in Fig. 3.
after HPLC of fresh bile samples revealed that with the intervals calculations were based on the assumption that the retinoyl /I-glucu-

[10-3H]retinoic acid after cumulative per cent

physiological tative examination of the retinoyl glucuronide peaks obtained trans-retinoic acid, about 40% of excreted retinoyl glucuro-

nearly constant tion ceases 12 h after dosing (Table II), the rate of retinoyl glucuronide excretion stays

of excreted retinoyl glucuro-

DISCUSSION

bile production: approximately 200 times more retinoyl glucuroni-

dose of all-trans-[10-3H]retinoic acid. This relationship also holds whether the retinoyl glucuronides are obtained directly from fresh, deproteinized bile or whether they are prepared by extracting the bile with 1-butanol and prepurifying it on Sephadex LH-20 columns. The similarity in the all-trans to 13-cis ratios obtained by the two different isolation procedures suggests that isomerization of retinoyl glucuronides is minimal during the isolation procedure and that the appearance of the 13-cis-retinoyl glucuronide in bile is the result of an in vivo production of this metabolite from all-trans-retinoic acid. Studies with retinoyl glucuronides obtained from the small intestine (11) confirm our present observations.

The excretion of retinoic acid metabolites into the bile has been studied recently by several investigators (7, 8). The findings confirm the original observations that retinoyl glucuronide is a biliary metabolite of retinoic acid (9), but demonstrate it to be only a minor component of the retinoic acid metabolite pool. These data are substantiated by our present findings. We find that retinoyl glucuronide represents only 10% of the dose radioactivity 24 h after a pharmacological dose of all-trans-retinoic acid. Only 10.3% of the biliary metabolites of retinoic acid are in the form of retinoyl glucu-

The physiological significance of retinoyl glucuronides in the bile is not clear. The biological activity of the purified retinoyl glucuronides has the same specific radioactivity of the injected all-truns-

9.  Excretion of retinoyl glucuronides into bile

The experimental details are described in Tables I and II. The calculations were based on the assumption that the retinoyl β-glucu-

TABLE III

Composition of Retinoyl Glucuronides in Bile—A quanti-

tative examination of the retinoyl glucuronide peaks obtained after HPLC of fresh bile samples revealed that with the physiological as well as with the pharmacological dose of all-

trans-retinoic acid, about 40% of excreted retinoyl glucuro-

nides are in the 13-cis form and 60% are in the form of all-

trans-retinoyl glucuronides. This relationship also holds

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