Induction of Osteogenic Sarcomas and Tumors of the Hepatobiliary System in Nonhuman Primates with Aflatoxin B₁

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ABSTRACT

The carcinogenicity of aflatoxin B₁ (AFB₁) has been under evaluation in nonhuman primates for the past 13 years. A total of 47 Old World monkeys, chiefly rhesus and cynomolgus, have received AFB₁, i.p. (0.125 to 0.25 mg/kg) and/or p.o. (0.1 to 0.8 mg/kg) for 2 months or longer, and 12 are currently alive and without evidence of tumor. Thirteen of the 35 monkeys necropsied to date (37%) developed one or more malignant neoplasms, yielding an overall tumor incidence of 28%. Five of the neoplasms were primary liver tumors (2 hepatocellular carcinomas and 3 hemangioendothelial sarcomas), and 2 cases of osteogenic sarcoma were found. Other tumors noted were 6 carcinomas of the gall bladder or bile duct, 3 tumors of the pancreas or its ducts, and one papillary Grade I carcinoma of the urinary bladder. The tumors developed in animals receiving an average total AFB₁ dose of 709 mg (range, 0.35 to 1368 mg) for an average of 55 months (range, 2 to 141 months). Our results indicate that AFB₁ is a potent hepatotoxin and carcinogen in nonhuman primates and further support the hypothesis that humans exposed to this substance may be at risk of developing cancer.

INTRODUCTION

The carcinogenic effects of AFB₁ are being evaluated in nonhuman primates. We report previously (3, 4) that 3 of 42 monkeys (7%) necropsied after receiving treatment with AFB₁ for longer than 2 years developed malignant primary liver tumors. The present report is an update of that study and describes 14 malignant tumors developing in 10 additional monkeys receiving long-term treatment with AFB₁.

MATERIALS AND METHODS

The monkey colony consists of 540 animals and is composed of rhesus (Macaca mulatta), cynomolgus (Macaca fascicularis), and African green (Cercopithecus aethiops) monkeys. Details of maintenance and management procedures and of the method used to rear neonates have been described elsewhere (1, 13). Briefly, monkeys are separated from their mothers a few hr postpartum and hand reared in a nursery. They receive Similac formula until the age of 6 months and are then maintained on a diet of Purina monkey chow supplemented by one-half an apple and a vitamin sandwich (13) each day.

The monkeys are housed individually, and various clinical, hematological, and biochemical parameters are monitored to evaluate their general health. Tuberculin skin testing is done bimonthly. Blood is collected weekly or biweekly from a femoral vein into heparinized tubes. Routine hematological examinations (hematocrit, RBC, WBC, platelet counts, hemoglobin levels, and differential counts), and other clinical tests including alkaline phosphatase, total bilirubin, serum glutamic-pyruvic transaminase, and serum glutamine-oxaloacetic transaminase are performed on all treated and control monkeys. Serum is also screened for the presence of AFP by double diffusion in agar gel with adsorbed antisera to AFP and control serum. Further quantification of AFP in positive specimens is accomplished using a double-antibody radioimmune assay (27). The lower limit of sensitivity for the standard curve is 5 ng/ml. Serum AFP levels in control monkeys average 15.5 ng/ml for rhesus and 13.0 ng/ml for cynomolgus.

AFB₁ (Calbiochem, Los Angeles, Calif., and Makor Chemicals Ltd., Jerusalem, Israel) is dissolved in a minimum of DMSO and administered according to a variety of schedules by i.p. injection, nasogastric intubation, or by inclusion on a vitamin sandwich. The amount of DMSO does not exceed 0.2 ml/kg body weight. The control population includes 20 DMSO-treated monkeys and a total of 191 untreated breeder monkeys. The vehicle-treated control monkeys receive weekly doses of DMSO (0.2 ml/kg) by intubation. Drug or vehicle treatment usually begins within 10 days after birth and continues indefinitely or until tumor is detected.

When clinical evidence of liver lesions or an elevation of serum AFP appears, a laparotomy is performed under phenylcyclidine hydrochloride or ketamine hydrochloride anesthesia, and all lobes of the liver are carefully inspected for gross pathological changes. When such changes are found, a wedge biopsy of the affected lobe or apparent tumor is performed. Monkeys that die or are sacrificed are carefully necropsied, and the following tissues and organs are excised and placed in buffered formalin: brain; pituitary; salivary gland; thyroid; parathyroid; thymus; tongue; cheek pouch; trachea; esophagus; lung; heart; aorta; liver; gall bladder; spleen; kidney; adrenal; stomach; pancreas; duodenum; jejunum; ileum; large intestine; lymph node; urinary bladder; testes; prostate; seminal vesicle (or ovary and uterus); skin; long bone; bone marrow; and tumor (tissue or mass). Paraffin sections are prepared for microscopic evaluation and stained with hematoxylin and eosin. Selected

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specimens are also stained with periodic acid-Schiff, and frozen sections, when made, are stained with Oil Red 0.

RESULTS

A total of 47 monkeys survived at least 2 months after the first dose of AFB₁. and 35 of these animals have thus far been necropsied. Twenty-two of the 35 monkeys showed no evidence of tumor upon histopathological examination of tissue following necropsy. These animals have been arbitrarily divided into 2 groups: those necropsied after receiving AFB₁ for less than 2 years; and those necropsied after receiving AFB₁ for longer than 2 years. Eleven monkeys survived between 2 and 21 months after initiation of AFB₁ treatment (Table 1). These monkeys received AFB₁ according to a variety of dosing schedules by either i.p. or p.o. (intubation or on vitamin sandwich) routes; total AFB₁ doses given the monkeys ranged from 0.08 to 28.88 mg. Seven of 11 monkeys in this group showed evidence of hepatic damage, with toxic hepatitis being the most frequent liver lesion found. However, the severity of the liver lesions did not appear to follow a close dose-response pattern. Thus, toxic hepatitis was detected upon histopathological examination of liver from 4 of 6 monkeys receiving less than 1 mg of AFB₁, whereas no evidence of such damage was found in Monkeys 687I, 446F, and 519G given doses of 4.37, 5.00, and 28.88 mg of AFB₁, respectively. The toxic hepatitis noted in the monkeys showed a wide range of severity. Liver tissue from Monkey 689I (0.35 mg of AFB₁) showed mild toxic hepatitis, whereas Monkey 532G developed severe toxic hepatitis after receiving a total AFB₁ dose of 0.64 mg. The liver lesions (Fig. 1) were characterized by necrosis of hepatic cells; those hepatocytes remaining showed swollen, deeply eosinophilic cytoplasm with frequent vacuoles. Lymphocytic infiltration around the necrotic cells was present, but there was very little formation of pseudotubules. Aside from liver lesions, the most common findings at necropsy of these monkeys were related to the respiratory system, and included bronchopneumonia and pulmonary congestion and edema.

Eleven monkeys were necropsied after receiving AFB₁ for periods ranging from 39 to 141 months and were found to be free of tumor (Table 2). Three of these animals were given doses i.p., 7 were given doses p.o., and one received AFB₁ both i.p. and p.o. Total AFB₁ doses given this group of animals ranged between 53.32 and 1368.69 mg. All but 2 of the monkeys showed histopathological evidence of liver damage, most frequently toxic hepatitis. In 2 cases with toxic hepatitis (Monkeys 587G and 527G), histopathological examination revealed the presence of hyperplastic liver nodules. Liver cirrhosis was found in 3 of the monkeys in this group, and in one case hyperplastic liver nodules were also present. Complications attributable to repeated i.p. injections (e.g., intestinal adhesions and obstruction) were noted in 3 of the 4 monkeys treated by this route. To date, 13 of the 35 necropsied monkeys (37%) have developed malignant tumors following AFB₁ treatment (Table 3). This represents 26% of all monkeys receiving AFB₁. In contrast, 68 nontreated breeder monkeys and vehicle-treated controls have died during this time period, of which 4 (5.9%) were found to have malignant tumors. The 4 monkeys (3 cases of malignant lymphoma in African green monkeys and one case of a gall bladder carcinoma in a 10-year-old rhesus monkey) represent 1.9% of all control and breeder monkeys maintained during this time in our monkey colony. Table 4 summarizes data for the 13 monkeys developing one or more malignant neoplasms after AFB₁ treatment.

The tumor-bearing monkeys received AFB₁ for periods of 47 to 147 months (average, 114 months). The total AFB₁ dose given these monkeys averaged 708.95 mg (range, 99.18 to 1354.24 mg). Five animals received AFB₁ both p.o. and i.p.; 8 received AFB₁ by the p.o. route only. The tumors developing in Monkeys 692I, 680H, and 454F have been described in detail in previous publications (3, 4) and are listed in the table for purposes of completeness only.

More than one primary tumor developed in 3 (Monkeys 590G, 683I, and 473F) of the 13 monkeys. Monkey 590G became inactive and developed a poor appetite approximately 2 years after receiving a total dose of 2.5 mg AFB₁ i.p. over a period of 4 months. A tumor developed in this monkey which was not described in previous publications (3, 4) and is listed in the table.

Table 1

<table>
<thead>
<tr>
<th>Monkey</th>
<th>Species</th>
<th>Sex</th>
<th>Mos. on AFB₁</th>
<th>Route</th>
<th>Total AFB dose (mg)</th>
<th>Liver lesions</th>
<th>Other findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>588G</td>
<td>Rh</td>
<td>M</td>
<td>2.5</td>
<td>i.p.</td>
<td>0.08</td>
<td>Infiltration</td>
<td>Bronchopneumonia</td>
</tr>
<tr>
<td>589G</td>
<td>Cy</td>
<td>M</td>
<td>2.5</td>
<td>i.p.</td>
<td>0.12</td>
<td>None</td>
<td>Diarrhea; pulmonary emphysema</td>
</tr>
<tr>
<td>689H</td>
<td>Cy</td>
<td>F</td>
<td>2</td>
<td>i.p.</td>
<td>0.35</td>
<td>Toxic hepatitis</td>
<td>Pneumonia; pulmonary congestion and edema</td>
</tr>
<tr>
<td>531G</td>
<td>Rh</td>
<td>F</td>
<td>2</td>
<td>p.o.</td>
<td>0.55</td>
<td>Toxic hepatitis</td>
<td>Pneumonia</td>
</tr>
<tr>
<td>440F</td>
<td>Rh</td>
<td>F</td>
<td>2</td>
<td>p.o.</td>
<td>0.60</td>
<td>Toxic hepatitis; fatty degeneration</td>
<td>Pulmonary edema</td>
</tr>
<tr>
<td>532G</td>
<td>Rh</td>
<td>M</td>
<td>2</td>
<td>p.o.</td>
<td>0.64</td>
<td>Toxic hepatitis</td>
<td>Pneumonia</td>
</tr>
<tr>
<td>516G</td>
<td>Rh</td>
<td>M</td>
<td>5</td>
<td>p.o.</td>
<td>4.35</td>
<td>Toxic hepatitis</td>
<td>Ileoclitis</td>
</tr>
<tr>
<td>687I</td>
<td>Rh</td>
<td>M</td>
<td>6</td>
<td>i.p.</td>
<td>4.37</td>
<td>None</td>
<td>Pneumonia and pulmonary emphysema; ileoclitis</td>
</tr>
<tr>
<td>446F</td>
<td>Rh</td>
<td>F</td>
<td>5</td>
<td>p.o.</td>
<td>5.00</td>
<td>None</td>
<td>Esophagitis, pulmonary congestion and edema</td>
</tr>
<tr>
<td>686I</td>
<td>Rh</td>
<td>F</td>
<td>13</td>
<td>i.p.</td>
<td>11.70</td>
<td>Hyperplastic nodules</td>
<td>Perforation of stomach</td>
</tr>
<tr>
<td>519G</td>
<td>Rh</td>
<td>M</td>
<td>21</td>
<td>p.o.</td>
<td>28.88</td>
<td>None</td>
<td>Pulmonary congestion and edema</td>
</tr>
</tbody>
</table>

* Rh, rhesus; Cy, cynomolgus.
6 months prior to death. An elevation in the blood urea nitrogen (69.5 mg/100 ml) was noted on the day before the monkey died, but AFP levels were within normal limits. Histopathological examination of tissue from this animal revealed an undifferentiated neoplasm of the pancreas. The tumor was composed of a proliferation of spindle-shaped cells surrounding, but not destroying, acini and islets of Langerhans. In some areas, the proliferation of spindle-shaped cells surrounding, but not destroying, acini and islets of Langerhans.

Table 2
Histopathological findings in monkeys without tumor receiving AFB, for 39 to 147 months

<table>
<thead>
<tr>
<th>Monkey</th>
<th>Species</th>
<th>Sex</th>
<th>Mos. on AFB</th>
<th>Route</th>
<th>Total AFB dose (mg)</th>
<th>Liver lesions</th>
<th>Other findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>668I</td>
<td>Cy</td>
<td>F</td>
<td>46</td>
<td>i.p.</td>
<td>53.32</td>
<td>Cirrhosis with hyperplastic nodules</td>
<td>Intestinal obstruction</td>
</tr>
<tr>
<td>576G</td>
<td>Cy</td>
<td>M</td>
<td>45</td>
<td>i.p.</td>
<td>56.89</td>
<td>None</td>
<td>Intestinal obstruction</td>
</tr>
<tr>
<td>522G</td>
<td>Rh</td>
<td>F</td>
<td>39</td>
<td>p.o.</td>
<td>163.39</td>
<td>Toxic hepatitis with centrilobular necrosis</td>
<td>Pulmonary edema and congestion</td>
</tr>
<tr>
<td>486F</td>
<td>Cy</td>
<td>M</td>
<td>64</td>
<td>i.p.</td>
<td>220.04</td>
<td>Toxic hepatitis</td>
<td>Intestinal adhesions</td>
</tr>
<tr>
<td>587G</td>
<td>Rh</td>
<td>M</td>
<td>121</td>
<td>i.p. and p.o.</td>
<td>513.14</td>
<td>Toxic hepatitis with hyperplastic nodules</td>
<td>None</td>
</tr>
<tr>
<td>521G</td>
<td>Rh</td>
<td>F</td>
<td>59</td>
<td>p.o.</td>
<td>514.77</td>
<td>None</td>
<td>Acute gastric dilatation</td>
</tr>
<tr>
<td>495F</td>
<td>Cy</td>
<td>F</td>
<td>89</td>
<td>p.o.</td>
<td>586.71</td>
<td>Toxic hepatitis</td>
<td>None</td>
</tr>
<tr>
<td>502F</td>
<td>Gr</td>
<td>M</td>
<td>117</td>
<td>p.o.</td>
<td>743.95</td>
<td>Cirrhosis</td>
<td>None</td>
</tr>
<tr>
<td>527G</td>
<td>Rh</td>
<td>M</td>
<td>65</td>
<td>p.o.</td>
<td>789.24</td>
<td>Toxic hepatitis with hyperplastic nodules</td>
<td>None</td>
</tr>
<tr>
<td>542G</td>
<td>Rh</td>
<td>F</td>
<td>120</td>
<td>p.o.</td>
<td>992.12</td>
<td>Micronodular cirrhosis</td>
<td>Biliary retention cyst</td>
</tr>
<tr>
<td>462F</td>
<td>Cy</td>
<td>M</td>
<td>141</td>
<td>p.o.</td>
<td>1368.69</td>
<td>Toxic hepatitis</td>
<td>None</td>
</tr>
</tbody>
</table>

*Cy, cynomolgus; Rh, rhesus; Gr, African green.

Table 3
Summary of control and AFB-treated monkeys, 1964 to 1978

<table>
<thead>
<tr>
<th>Group</th>
<th>No. alive</th>
<th>Without tumor</th>
<th>With tumor</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFB</td>
<td>12</td>
<td>22</td>
<td>13 (27.6)*</td>
<td>47</td>
</tr>
<tr>
<td>Control</td>
<td>143</td>
<td>64</td>
<td>4 (1.9)</td>
<td>211</td>
</tr>
</tbody>
</table>

*Numbers in parentheses, percentage of monkeys with tumor.

The second monkey (Monkey 683I) in which 2 primary tumors were diagnosed began to lose weight 20 months prior to diagnosis of tumor, but AFP levels remained negative throughout its lifetime. An osteogenic sarcoma of the distal radius developed in this monkey that was first observed as a hard and apparently painless swelling in the region of its wrist. The tumor grew rapidly, tripling in size in the 1-month period between the time it was first noted and the time the animal was sacrificed. Fig. 3 shows the radiographic appearance of the tumor. Necropsy and histological examination of tissue from this animal revealed a moderately well-differentiated adenocarcinoma of the common bile duct with extension to the gall bladder and the soft tissues of the liver hilum. In addition, an adenocarcinoma was found in the main pancreatic ducts; it was anatomically independent of the tumor noted in the intrahepatic biliary ducts.

The third monkey with 2 primary tumors, Monkey 473F, was noted to be pale, inactive, and without appetite and to have a markedly distended abdomen approximately 12.5 years after the first AFB dose. Over the next 4 days, approximately 1 liter of ascites fluid was removed from its peritoneal cavity. Laparotomy on the day prior to sacrifice revealed tumor in several lobes of the liver, although serum AFP levels were within normal limits. Two apparently independent tumors were diagnosed in this animal. One tumor was a well-differentiated adenocarcinoma of the hepatic duct (Fig. 4); this tumor invaded the liver parenchyma (Fig. 5) and the portal vein and had metastasized to numerous locations including the lungs, omentum, peritoneum, broad ligament of the uterus, and the urinary bladder.

The first AFB, dose. Over the next 4 days, approximately 1 liter of ascites fluid was removed from its peritoneal cavity. Laparotomy on the day prior to sacrifice revealed tumor in several lobes of the liver, although serum AFP levels were within normal limits. Two apparently independent tumors were diagnosed in this animal. One tumor was a well-differentiated adenocarcinoma of the hepatic duct (Fig. 4); this tumor invaded the liver parenchyma (Fig. 5) and the portal vein and had metastasized to numerous locations including the lungs, omentum, peritoneum, broad ligament of the uterus, and the urinary bladder.

The third monkey with 2 primary tumors, Monkey 473F, was noted to be pale, inactive, and without appetite and to have a markedly distended abdomen approximately 12.5 years after the first AFB dose. Over the next 4 days, approximately 1 liter of ascites fluid was removed from its peritoneal cavity. Laparotomy on the day prior to sacrifice revealed tumor in several lobes of the liver, although serum AFP levels were within normal limits. Two apparently independent tumors were diagnosed in this animal. One tumor was a well-differentiated adenocarcinoma of the hepatic duct (Fig. 4); this tumor invaded the liver parenchyma (Fig. 5) and the portal vein and had metastasized to numerous locations including the lungs, omentum, peritoneum, broad ligament of the uterus, and the urinary bladder.

The third monkey with 2 primary tumors, Monkey 473F, was noted to be pale, inactive, and without appetite and to have a markedly distended abdomen approximately 12.5 years after the first AFB dose. Over the next 4 days, approximately 1 liter of ascites fluid was removed from its peritoneal cavity. Laparotomy on the day prior to sacrifice revealed tumor in several lobes of the liver, although serum AFP levels were within normal limits. Two apparently independent tumors were diagnosed in this animal. One tumor was a well-differentiated adenocarcinoma of the hepatic duct (Fig. 4); this tumor invaded the liver parenchyma (Fig. 5) and the portal vein and had metastasized to numerous locations including the lungs, omentum, peritoneum, broad ligament of the uterus, and the urinary bladder.

The third monkey with 2 primary tumors, Monkey 473F, was noted to be pale, inactive, and without appetite and to have a markedly distended abdomen approximately 12.5 years after the first AFB dose. Over the next 4 days, approximately 1 liter of ascites fluid was removed from its peritoneal cavity. Laparotomy on the day prior to sacrifice revealed tumor in several lobes of the liver, although serum AFP levels were within normal limits. Two apparently independent tumors were diagnosed in this animal. One tumor was a well-differentiated adenocarcinoma of the hepatic duct (Fig. 4); this tumor invaded the liver parenchyma (Fig. 5) and the portal vein and had metastasized to numerous locations including the lungs, omentum, peritoneum, broad ligament of the uterus, and the urinary bladder.
cell carcinoma of the hepatic and common bile ducts. The poorly differentiated tumor invaded the wall of the common bile duct and projected in a polypoid manner into the lumen of some of the large bile ducts. It was composed primarily of undifferentiated spindle cells with occasional glandular differentiation (Fig. 8). Evidence of cirrhosis was also found in sections of liver from this animal (Fig. 9).

Monkey 535G developed marked jaundice 10 days before it was sacrificed; at necropsy, the neck of the gall bladder was found to be inactive and to have a poor appetite although not noted to be inactive and to have a poor appetite although. Evidence of cirrhosis was also found in sections of liver from this animal (Fig. 9).

An elevation in the serum AFP level (450 ng/ml) noted 112 days on alternate weeks. Dosing began within 9 days of birth for all monkeys. Two days prior to sacrifice, the animal developed severe jaundice. At necropsy, tumor almost completely replacing the liver was found, which corresponded histologically to an hemangioendothelial sarcoma; multiple tumor metastases were found in the lungs. Sections of liver not involved with tumor showed toxic hepatitis.

One week before the death of Monkey 471F, the animal was noted to be inactive and to have a poor appetite although hematologist and clinical chemistry values were within normal limits. Histological examination of tissue from this animal revealed an hemangioendothelial sarcoma of the liver with multiple metastases to the lung; areas of liver not involved with tumor showed micronodular cirrhosis. Micronodular cirrhosis with severe toxic hepatitis; pelvic endometriosis. Toxic hepatitis.

Monkey 479F became jaundiced about 2 months before its death, but AFP levels remained within normal limits throughout its life. A laparotomy was performed 6 years after initiation of AFB treatment, but no gross evidence of tumor was found. At necropsy of this animal, a mass of hard white tissue was noted in the region of the gall bladder, which was sacrificed, at which time AFP levels were within normal limits. Two days prior to sacrifice, the animal developed severe jaundice. At necropsy, tumor almost completely replacing the liver was found, which corresponded histologically to an hemangioendothelial sarcoma; multiple tumor metastases were found in the lungs. Sections of liver not involved with tumor showed micronodular cirrhosis with severe toxic hepatitis.
classified as a well-differentiated gall bladder adenocarcinoma (Fig. 10). The tumor had invaded the liver parenchyma and had metastasized to the lungs. Sections of liver from areas not involved with tumor showed toxic hepatitis.

Liver biopsies performed 20, 52, and 85 months after Monkey 374E was given the first dose of AFB1, failed to yield evidence of tumor, although toxic hepatitis was evident in sections of liver taken at the 2 later biopsies. AFB1 levels remained within normal limits throughout the life of this animal. Approximately 5 months before it was sacrificed, its body weight decreased from 8.6 kg to a terminal value of 5.7 kg. Marked jaundice developed, and a laparotomy was performed one week before sacrifice. Findings included dilation of the common bile duct, a heavily scarred gall bladder, and a shrunken and abnormally shaped liver, but no gross evidence of tumor was observed. However, following necropsy and histopathological examination of tissue from this animal, no tumor was found. Evaluation of tumor incidence as a function of treatment route revealed a significantly higher (p < 0.01) tumor incidence in monkeys receiving AFB1, both p.o. and i.p. compared to monkeys receiving AFB1 by i.p. injection, whereas 8 of 19 (42%) necropsied male monkeys developed tumors; 3 tumors of the pancreas or its ducts (one undifferentiated pleomorphic adenocarcinoma; 5 carcinomas of the cystic, hepatic, and/or common bile ducts (one spindle-cell carcinoma, and 4 adenocarcinomas); 1 tumor of the urinary bladder.

Twelve monkeys are currently receiving weekly doses of AFB1, (0.2 mg/kg) by intubation (Table 5). The total AFB1 dose ingested by these monkeys thus far averages 952.65 mg and ranges between 355.68 and 1377.24 mg. The monkeys have been receiving continuous treatment with AFB1, for periods ranging from 138 to 150 months (average, 142 months). All but 2 monkeys have received total doses of AFB1 exceeding the average total dose given the 13 monkeys which developed malignant tumors; none of the animals has developed clinical signs of illness.

Thus, 13 of 47 Old World monkeys treated with AFB1, have developed a total of 17 malignant neoplasms. These tumors included: 5 primary liver tumors (2 hepatocellular carcinomas and 3 hemangioendothelial sarcomas); one gall bladder adenocarcinoma; 5 carcinomas of the cystic, hepatic, and/or common bile ducts (one spindle-cell carcinoma, and 4 adenocarcinomas); 3 tumors of the pancreas or its ducts (one undifferentiated pleomorphic and 2 adenocarcinomas); 2 osteogenic sarcomas; and one papillary Grade 1 carcinoma of the urinary bladder.

No clear pattern emerged when tumor type was analyzed with regard to sex, subspecies, route of administration, or dose of AFB1, probably because of the relatively small numbers of tumor-bearing animals. The tumors developed in 8 of 22 (36%) necropsied rhesus monkeys, 4 of 11 (36%) necropsied cynomolgus monkeys, and in one of 2 (50%) necropsied African green monkeys. Evaluation of tumor incidence as a function of subspecies by x2 analysis failed to show significant differences (p > 0.9) in tumor incidence among the 3 groups. Five of 16 (31%) necropsied female monkeys and 8 of 19 (42%) necropsied male monkeys developed tumors; x2 analysis of tumor incidence in males and females failed to reveal a statistically significant (p > 0.30) sex difference. No tumors have developed in monkeys receiving AFB1, by i.p. injection, whereas 8 of 21 (38%) necropsied monkeys treated p.o. developed tumors, as have 5 of 6 (83%) of animals treated both p.o. and i.p. Evaluation of tumor incidence as a function of treatment route revealed a significantly higher (p < 0.01) tumor incidence in monkeys receiving AFB1, both p.o. and i.p. The monkeys developing tumor showed individual variation with regard to latent period and cumulative dose ingested.

Although the average AFB1 dose administered to the monkeys was 708.95 mg, one monkey developed tumor after receiving only 99.18 mg of compound. All but 2 of the monkeys without tumor receiving AFB1, longer than 2 years had ingested in excess of 99 mg of compound, and 4 of these had received total AFB1 doses exceeding the average dose given the tumor-bearing animals. Furthermore, although the dosing interval for monkeys developing tumors averaged 114 months, the first AFB1-induced tumor appeared after only 47 months of treatment.

DISCUSSION

AFB1 is hepatotoxic and carcinogenic in many species of laboratory animals, including nonhuman primates. However, a considerable amount of species variation exists with regard to susceptibility to the carcinogenic and other adverse effects of aflatoxins. The mouse appears to be relatively resistant to the hepatotoxic and carcinogenic effects of aflatoxins (19, 26), whereas the effective hepatocarcinogenic dose of AFB1, in rats has been estimated to be 50 µg/kg (9). The Rainbow trout seems markedly more sensitive than do rodents to the hepatocarcinogenic effects of aflatoxins, inasmuch as doses of 0.2 to 2.0 µg AFB1 per kg induce a high incidence of liver tumors in this species (6, 7).

Information has begun to accumulate on the hepatotoxicity and carcinogenicity of aflatoxins in human and nonhuman primates. The studies of Reddy et al. (28) have shown that the prosimian primate Tupaia glis, or tree shrew, is extremely sensitive to AFB1-induced hepatotoxicity and hepatocarcinogenicity. All 6 females and 3 of 6 males developed hepatocellular carcinomas between 74 and 172 months after the first dose of AFB1; the cumulative doses given the animals developing tumors ranged between 24 and 66 mg. The predominant lesions found at necropsy were related to the liver, and no changes in sections from the biliary tract or pancreas were described. Liver changes noted ranged from diffuse fatty metamorphosis of liver parenchyma in animals that died early in the course of the experiment to severe postnecrotic scarring, stellate scarring of isolated portal tracts accompanied by oval cell proliferation, necrosis of isolated liver cells in periportal liver cords, and mononuclear cell infiltrates in animals surviving up to 172 weeks. Considerable individual variation existed with regard to the response of the tree shrew liver to AFB1, and the

NOVEMBER 1979 4549
degree of liver damage did not correspond to the cumulative dose of carcinogen ingested (28).

The first reports on the effects of aflatoxins in higher primates (Old World monkeys) described results from acute and subacute feeding studies which were probably terminated too early for a carcinogenic effect to become apparent. The histopathological lesions noted in liver from treated animals were widely variable in severity and, as was the case with tree shrews, could not be correlated with cumulative aflatoxin dose. Unlike the tree shrew, however, proliferation of bile duct epithelium was a consistent finding in all of the studies. Thus, Madhavan et al. (18) gave a group of young rhesus monkeys daily doses of aflatoxin (0.5 and 1.0 mg) and found severe fatty metamorphosis and portal fibrosis in the animals within 4 weeks of the first dose of aflatoxin. A striking proliferation of ductules was noted in the portal tracts, along with fibrosis and chronic inflammatory cells. The histogenesis of the hepatic fibrosis was explained in its entirety on the basis of portal inflammation, bile duct proliferation, and periductular fibrosis. In a study reported by Cuthbertson et al. (10), a group of cynomolgus monkeys was fed a diet of groundnut meal containing aflatoxins for up to 3 years. A variety of hepatic lesions was noted at necropsy, including central zonal liver cell necrosis or degeneration accompanied by liver cell regeneration and bile duct and fibroblastic proliferation. Liver cell atypia and fatty change was also found in the animals. Similar observations were made by Deo et al. (11), who fed rhesus monkeys aflatoxins for periods up to 2 years. A triad of histological changes consisting of large hyperchromatic liver cells, bile duct epithelial and stromal proliferation, and condensation around proliferated ductular cells was a frequent finding. However, no changes were noted in other animals given identical quantities of aflatoxin for the same length of time. Bourgeois et al. (8) evaluated the histological changes developing in the livers of monkeys killed one week after a single dose of AFB1 (0.5 to 40.5 mg/kg). At doses exceeding 1.5 mg/kg, the liver changes they found included fatty degeneration of hepatocytes, decreased liver glycogen, liver cell necrosis, and hyperplasia of the bile duct epithelium. Similar histological changes were found in the monkeys in the present study, although considerable individual variation in sensitivity to AFB1 was noted. In the tumor-free monkeys necropsied thus far, the hepatic lesions have not correlated well with the total AFB1 dose administered. Thus, toxic hepatitis was present in liver from some monkeys receiving a total AFB1 dose of less than 1 mg, whereas no liver lesions were noted in other animals which had ingested as much as 515 mg of AFB1.

Studies in which aflatoxin has been administered to Old World monkeys for relatively prolonged periods indicate that it is a carcinogen as well as an hepatotoxic in higher primates. Thus, Tilak (30) reported that a female rhesus monkey developed a cholangiocarcinoma of the intrahepatic bile ducts after receiving a mixture of aflatoxins for 5.5 years. A male rhesus monkey developed a primary hepatocellular carcinoma after prolonged treatment with a mixture of aflatoxins (12).

Some tentative conclusions can now be drawn to the carcinogenicity and hepatotoxicity of aflatoxins in various animal species. First, although the degree of liver damage in rats, rainbow trout, and marmosets appears to closely parallel the cumulative dose of aflatoxin received (17, 20, 21), this does not seem to be the case in either tree shrews or Old World monkeys. Second, the type of histological lesions induced by aflatoxins appears to be dependent upon many variables, including the species. Thus, aflatoxins induce hepatocellular damage and primary liver carcinomas in rainbow trout, rats, and tree shrews, whereas the most striking and consistent lesions in Old World monkeys and in humans appear to be related to the biliary system. In many species of domestic animal, the subacute toxicity of aflatoxins is most consistently manifested as proliferation of the bile duct epithelium (32), and the duckling is particularly prone to develop this lesion following acute exposure to aflatoxins; in fact, the sensitivity of duckling bile duct epithelium provided the basis for bioassays of aflatoxin contamination of foodstuffs (5, 22). Bile duct lesions are also frequently found in cases of human aflatoxicosis. Histopathological examination of liver taken at autopsy of persons following an outbreak of aflatoxicosis in Western India revealed pathological changes similar to those in the monkeys in the present study, particularly bile duct proliferation with periductal fibrosis (14). The clinical features of the hepatitis that developed in these patients prior to autopsy included portal hypertension, jaundice, and rapidly developing ascites, and they were associated with a high mortality rate. Although the first 3 tumors that arose in our AFB1-treated monkeys were primary liver tumors (3, 4), 9 of the 14 tumors that subsequently emerged were malignant tumors of the biliary system or pancreas. The monkeys developing these tumors showed many of the clinical features of the hepatitis developing in patients exposed to aflatoxins, including jaundice and rapidly developing ascites.

Studies in rats have indicated a sex difference with regard to tumor induction by aflatoxins, with females showing greater resistance to hepatocarcinogenesis than males (33). This does not appear to be the case with either the tree shrew or the Old World monkey. In the present study, no sex differences were noted with regard to incidence or severity of liver lesions in tumor-free monkeys. Furthermore, neither the overall incidence of tumors nor the incidence of liver, biliary, or pancreatic tumors appeared to be sex related.

Thus, the response of the rat to aflatoxins appears to be somewhat different from that of the duckling, nonhuman primates, and humans. Furthermore, studies from this laboratory (2) have shown that prosimian primates, such as the tree shrew and galago, tend to resemble rats more closely than higher primates, such as Old World monkeys, with regard to response to some chemical carcinogens (e.g., polycyclic hydrocarbons). The present study provides further evidence for this, since a preponderance of the tumors induced in Old World monkeys by AFB1 were carcinomas of the biliary tract and pancreas, in contrast to the primary liver carcinomas induced in tree shrews and rats.

The development of the 2 osteogenic sarcomas in the AFB1-treated monkeys was an interesting finding. To our knowledge, aflatoxins have not been associated with this type of tumor in any other experimental animal or in humans. No cases of spontaneous osteogenic sarcomas have appeared in our monkey colony over the past 16 years, although 5 cases of spontaneous osteogenic sarcomas have been reported in other colonies of nonhuman primates (23). However, we recently reported finding osteogenic sarcomas in 2 monkeys receiving long-term treatment with procarbazine, a known chemical carcinogen (29); the sarcomas developed in the jaw and humerus of a female cynomolgus and a female rhesus monkey, respec-
tively. Thus, it appears that this relatively rare type of tumor can be induced in nonhuman primates by chemical carcinogens as well as by irradiation (15, 16, 24, 25, 31).

The present study clearly demonstrates that AFB	extsubscript{1} is a hepatotoxin and carcinogen in Old World monkeys. The results not only lend additional support to the hypothesis that AFB	extsubscript{1} is a hepatocarcinogen in humans but also raise the possibility that this chemical may play a role in the etiology of human pancreatic and gall bladder carcinoma and osteogenic sarcoma.

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Fig. 1. Liver from Monkey 532G, showing severe toxic hepatitis. H & E, x 100.

Fig. 2. Intramucosal Grade I papillary carcinomas of the urinary bladder from Monkey 590G. H & E, x 40.

Fig. 3. X-Ray of osteogenic sarcoma of the distal radius that developed in Monkey 6831.

Fig. 4. Adenocarcinoma of hepatic duct developing in Monkey 473F. H & E, x 40.
Effects of AFB₁ in Nonhuman Primates

Fig. 5. Bile duct adenocarcinoma invading liver parenchyma in Monkey 473F. H & E, × 100.

Fig. 6. Pancreatic duct adenocarcinoma invading the parenchyma in Monkey 473F. H & E, × 100.

Fig. 7. Osteogenic sarcoma of the tibia of Monkey 582G. H & E, × 100.

Fig. 8. Spindle-cell carcinoma of the hepatic and common bile ducts of Monkey 518G. H & E, × 100.
Fig. 9. Liver from Monkey 518G, showing cirrhosis of the liver. H & E, × 40.
Fig. 10. Well-differentiated gall bladder adenocarcinoma in Monkey 479F. H & E, × 40.
Fig. 11. Adenocarcinoma of the common bile duct and ampulla of Vater found in Monkey 374E. H & E, × 40.
Induction of Osteogenic Sarcomas and Tumors of the Hepatobiliary System in Nonhuman Primates with Aflatoxin B₁

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