Oncogenes in Hematopoietic and Hepatic Fish Neoplasms

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Abstract

Neoplastic transformation of cells has often been associated with changes in cellular oncogenes. While much information has been collected in mammalian systems, relatively little is known about the molecular basis of tumor progression in lower vertebrates. For our studies, tumors were collected from feral northern pike (Esox lucius) from Ostego Lake, MI, where the local population exhibited a 15% incidence of large external lymphomas. In laboratory studies, tumors were induced under controlled conditions by known mammalian carcinogens in the Japanese medaka (Oryzias latipes), a small aquarium fish widely used in carcinogenicity studies. DNA isolated from these tumors was assayed for transforming sequences by transfection into NIH3T3 cells. DNAs from the northern pike lymphomas and the chemically induced tumors in the medaka were able to transform NIH3T3 cells and induce tumors in athymic mice. The results of our studies to date are summarized here, together with the current status of oncogene activation in other fish systems.

Introduction

Teleost fish constitute the largest and most diverse class of vertebrates, with over 20,000 known species. Their diversity and place in the phylogenetic tree make them ideal subjects for comparative carcinogenesis studies which may allow more insight into basic mechanisms than studies limited to mammalian models alone. Only relatively recently have fish begun to gain importance for use in carcinogenicity studies. Fish tumor investigation is now seen as an integral part of the basic, biological approach to elucidating common mechanisms of cancer at different phylogenetic levels. Neoplasms have been reported in virtually all the major organs and cell types in many species of fish. While the structure of some organs in fish differs considerably from those in mammals, tumors are often very similar histologically and may be classified by criteria similar to those used in human tumor diagnosis.

The high incidence of tumors in feral fish and chemical induction of tumors in fish in the laboratory have been well documented (1, 2). However, very little is known about the molecular basis of carcinogenesis in these animals. It is important to emphasize that, even though exposure to chemical carcinogens is highly correlated with tumor incidence, it is extremely difficult to prove causality. One way that the etiology of these tumors may be assessed is through the application of molecular methods. Central to such an evaluation is the identification of oncogene sequences and characterization of their role in tumor formation.

Ironically, probably the first “oncogene” ever to be described was in a fish. Following the first report of melanoma formation in swordtail-platyfish (Xiphophorus) hybrids in 1928, a series of elegant, classical genetic studies by Gordon, Anders, Schartl, and others led to the postulation of a “tumor” gene, tu (3). tu was recently cloned and has been identified as an oncogene. It codes for a novel RTK, closely related to the receptor for epidermal growth factor (4). The first oncogenes from fish identified by cloning and sequence analysis were the myc gene in rainbow trout (5) and the ras gene from goldfish (6). The isolation and expression of several additional oncogenes have since been reported from Xiphophorus (7). The elevated expression of the src gene was noted in Xiphophorus melanomas, although it was demonstrated not to be directly involved in tumor formation (8).

More recently, McMahon et al. (9) reported a point mutation in a c-K-ras gene from a liver tumor in winter flounder (Pseudopleuronectes americanus), identified through NIH3T3 transfection analysis. They observed a single G → T base transversion in the second base of the 12th codon, the same type of mutation reported in ras genes from some chemically induced rodent tumors (10). Virgin et al. (11) have also reported an activated K-ras in Atlantic tomcod (Microgadus tomcod) liver tumors.

Work in our laboratory indicated that DNAs isolated from tumors in feral northern pike (Esox lucius), as well as DNAs from chemically induced tumors in laboratory medaka (Oryzias latipes), are also able to transform NIH3T3 cells (12, 13).

In this paper, we report the results of our transfection studies and summarize the studies to date on fish oncogenes in hematopoietic and hepatic neoplasms.

Materials and Methods

Fish. Tumors were collected from northern pike from Ostego Lake, Gaylord, MI. Over 20% of the fish in this area exhibited large external lesions, identified as lymphomas.

Tumors were chemically induced in the medaka in two different experiments. In the first, a group of 14-day-old medaka fry were exposed for 48 h to 200 mg/liter of DEN dissolved in water. Animals were transferred to aquaria containing clean water for a period of 360 days. They were then removed, anesthetized, and sacrificed. Livers from these animals were excised, and small portions of each liver were individually fixed in Bouin’s solution and subsequently stained with hematoxylin-eosin for histopathological assessment. The remaining tissue was frozen immediately in liquid nitrogen and stored at −70°C until DNA was extracted.

In a second experiment, 8-day-old medaka embryos were exposed prior to hatch for 4 h to 50 mg/liter of MAMac dissolved in water. A single animal was sacrificed, and a grossly observable tumor was removed from the caudal peduncle. This tissue was then treated as described above for the DEN-induced lesions.

Transfection Analysis. DNA was prepared by quick Dounce homogenization (12). Integrity of the DNA was determined by analysis on a 0.35% agarose gel, where it migrated more slowly than did intact λ-phage DNA. The transfection procedure was modified from that of Graham and van der Eb (14) and is presented elsewhere (12). Briefly, high-molecular-weight fish DNA was cotransfected with pSV2neo in the presence of calcium phosphate into NIH3T3 cells (strain 490N3T). Cells were grown under drug selection with G418 (Geneticin; Gibco), pooled, and replated for three assays. Cells were grown to confluency and examined for foci of altered morphology. A second aliquot of the

1 The abbreviations used are: RTK, tyrosine kinase receptor; DEN, diethylnitrosamine; MAMac, methylazoxymethanol acetate.
same pool was examined for tumorigenicity by injection into athymic mice (15). A third aliquot was replated and grown in defined serum-free medium (QBSF; Quality Biologicals) in a colony selection assay. Foci and colonies were picked and expanded. Tumors were excised from nude mice. DNA was prepared as described earlier (12).

Characterization of Transformed Cells. Transformed cells were grown in soft agar to test for anchorage dependence (16). The maximum stringency necessary to detect oncogene sequences by Southern analysis in fish DNA from normal tissue was determined in pilot experiments. Transfected DNA was then analyzed on Southern blots (17) which were hybridized to known oncogene probes at the predetermined appropriate stringency. These were examined for homology of the fish transforming sequences. The presence of fish sequences in DNA from transformed cells was examined on Southern blots of transfectant DNA digests by hybridization of these to radiolabeled (18) high-molecular-weight medaka genomic DNA.

**Results**

**Northern Pike Transfections.** In primary transfaction experiments, foci of transformed cells were detected in three of four plates that were transfected with DNA from pike tumors and grown in the presence of dexamethasone (Table 1). No foci were observed in control plates. Cells from individual foci were picked, expanded, and replated in a soft agar assay. They were able to form small colonies, characteristic of transformed mouse fibroblasts. Transformation efficiency increased in a secondary transfaction assay. Cells from foci isolated from this transfaction were also able to form colonies in soft agar, at a relatively faster rate than the primary transfectants (Table 2). No homology was observed to known oncogene probes on Southern blots of digested DNA from transfected cells (data not shown).

**Medaka Transfections.** Results of the primary and secondary transfaction assays using medaka DNA are presented in Tables 3 and 4. DNA isolated from a DEN-induced cholangiocarcinoma was the most active in our assay, followed by DNA from animals withDEN-induced focal biliary hyperplasia. DNAs isolated from histologically normal or mildly abnormal, non-neoplastic liver from DEN-exposed fish were unable to transform NIH3T3 cells.

DNA from a MAMAc-induced rhabdomyosarcoma was unable to induce focus formation in the standard focus assay. However, three of four secondary transformants were able to grow in minimal media at very low serum levels, and two of these transformants were able to induce tumors in nude mice at frequencies and rates significantly higher than control cells (Table 4). Since only a single individual was examined, this experiment will be repeated.

In Southern analyses of DNA from foci cells, distinct bands which hybridized to radiolabeled medaka DNA were present in restriction digests of DNA from NIH3T3 cells transfected with fish tumor DNA (12). These bands were not present in DNA digests isolated from NIH3T3 cells alone or in NIH3T3 cells transfected with normal control fish DNA. In addition, in the original transfaction of medaka cholangiocarcinoma DNA, two plates which were independently transfected with this DNA were both highly transformed. DNA isolated from foci from these two plates showed overlapping fish-specific fragments on Southern blots. Efficiency of transformation has increased in secondary (Table 4) and tertiary transfactions (data not shown).

**Discussion**

While the detailed mechanisms of tumorigenesis are unknown, increasing evidence suggests that genetic alterations of cellular oncogenes are in part responsible for the neoplastic transformation of cells. Methods of activation include point mutations, inappropriate gene expression, chromosomal translocation, and gene amplification. Although much work has been

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**Table 1** Primary transfaction of northern pike DNA into NIH3T3 cells

<table>
<thead>
<tr>
<th>DNA source</th>
<th>Focus assay (foci/µg of DNA)</th>
<th>Relative colony growth in soft agar a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lymphoma</td>
<td>DCF5 0.19</td>
<td>+</td>
</tr>
<tr>
<td>Normal liver</td>
<td>0.01</td>
<td>0</td>
</tr>
</tbody>
</table>

a no growth; +, small colonies; ++, many colonies, comparable to positive control cells (mos- and H-ras-transformed NIH3T3 cells).

**Table 2** Colony formation in soft agar by cells transfected with northern pike DNA

<table>
<thead>
<tr>
<th>Cells b</th>
<th>Relative colony growth a</th>
</tr>
</thead>
<tbody>
<tr>
<td>TR13-16Aa (normal liver)</td>
<td>-</td>
</tr>
<tr>
<td>TR13-19Aa (lymphoma)</td>
<td>++</td>
</tr>
<tr>
<td>TR13-21Aa (lymphoma)</td>
<td>++</td>
</tr>
<tr>
<td>NIH3T3 cells</td>
<td>-</td>
</tr>
<tr>
<td>mos-transformed NIH3T3 cells</td>
<td>++</td>
</tr>
<tr>
<td>H-ras-transformed NIH3T3 cells</td>
<td>++</td>
</tr>
</tbody>
</table>

b Cells were expanded from foci isolated from a secondary transfaction of northern pike tumor and control DNA as indicated.

cells were expanded from foci isolated from a secondary transfaction of northern pike tumor and control DNA as indicated.

data not shown.

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S. M. Robertson, unpublished data.
ONCOGENES IN FISH TUMORS

Table 4 Summary of medaka secondary transfection analysis

<table>
<thead>
<tr>
<th>DNA source</th>
<th>Focus assay</th>
<th>Colony selection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DCF5</td>
<td>DCF5 + DEX</td>
</tr>
<tr>
<td>Untreated medaka controls</td>
<td>0.57</td>
<td>0</td>
</tr>
<tr>
<td>MAMAc-induced rhabdomyosarcoma</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DEN-induced focal biliary hyperplasia</td>
<td>0.77</td>
<td>0.53</td>
</tr>
<tr>
<td>DEN-induced cholangiocarcinoma</td>
<td>5.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

¹ Tumors at <5 wk postinjection. Data are summarized from Van Beneden et al. (12).
² DCF5, Dulbecco’s modified Eagle’s medium; DCF5 + DEX, DCF5 supplemented with dexamethasone; QBSF, Quality Biologicals Serum-free medium.

The table above summarizes the results of secondary transfection analysis using medaka cells. The focus assay data indicate the efficiency of transfection, while the colony selection data provide information on the integration and expression of the transfected DNA.

Results of our transfection assays indicate that DNA from fish tumors is capable of transforming NIH3T3 cells and inducing tumors in nude mice. The DNA isolated from the DEN-induced cholangiocarcinoma was the most active in our transfection assays. Secondary transfectants induced tumors in nude mice in 1.5 to 2.5 wk. DNA from the MAMAc-induced rhabdomyosarcoma was unable to induce foci. However, cells transfected with this DNA were able to grow in low (1%) serum media and induced tumors in nude mice at a level significantly higher than control cells.

We have not yet identified these oncogenes. Previous studies (12) have shown that fish sequences were present in DNA from transformed cells. They do not, based on Southern analysis, appear to be homologous to the known oncogenes that we examined. We are currently cloning this gene from a transformed cell-derived library.

Other studies have used transfection analysis to address the role of oncogenes in fish tumors. McMahon et al. (9) reported an activated K-ras in liver tumors of winter flounder. In five fish examined, they observed a single base change in the 12th codon, a region of frequent mutation in activated mammalian ras genes (10). The authors speculated that the presence of an activated oncogene may indicate exposure of the fish to polycyclic aromatic hydrocarbons known to be abundant in sediments at the collection site. An activated K-ras gene has also been reported from transfection analysis of Atlantic tomcod tumors (11). The tomcod is also a bottom-dwelling fish. Adult fish of >1 yr old exhibit about a 90% incidence of neoplasia in the Hudson River (22). Southern blots of DNA from transfected cells showed a unique band that hybridized to K-ras which was not present in NIH3T3 or tomcod DNA digests. This gene has not been sequenced, and no evidence was presented to confirm its identity as a tomcod c-ras.

Melanoma production in Xiphophorus hybrids is perhaps one of the most interesting fish systems in which oncogenes have been detected. The evidence for the presence of an oncogene was accumulated through years of classical genetic analysis and, more recently, by molecular techniques. In hybrid fish (X. maculatus × X. kelleri), the macromelanophores develop into malignant melanomas. This process results from abnormal regulation of the platfish tu gene. tu has been known for some time to be a dominant tumor gene (macromelanophore locus) and is under the control of the regulatory gene R which acts as a tumor suppressor gene. Repeated backcrossing eliminates the regulatory control and deregulates tu expression. The tu gene has been recently cloned and sequenced (4). It has a high degree of sequence homology to the RTKs and especially to the receptor for human epidermal growth factor. In addition to the oncogenic tu, now renamed Xmrk, on the sex chromosomes, another copy was detected at the INV locus and is thought to be a protooncogene. Expression of the Xmrk is correlated with the degree of malignancy.

While the study of tumorigenesis in fish at the molecular level still lags behind that of higher vertebrates, the studies summarized here (Table 5) indicate that considerable progress has been made in recent years. Studies of oncogenes and tumor progression in teleosts promise to shed some light on basic mechanisms of carcinogenesis and may reveal novel oncogenes that may not be detected by the exclusive use of mammalian models.

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