Significance of hepatic preneoplasia for cancer chemoprevention

P. Bannasch, D. Nehrbass and A. Kopp-Schnieder

Hepatic preneoplasia represents an early stage in neoplastic development, preceding both benign and malignant neoplasia. This applies particularly to foci of altered hepatocytes (FAH), that precede the manifestation of hepatocellular adenomas and carcinomas in all species investigated. Morphological, microbiological and molecular biological approaches in situ have provided evidence for striking similarities in specific changes of the cellular phenotype of preneoplastic FAH emerging in experimental and human hepatocarcinogenesis, irrespective of whether this was elicited by chemicals, hormones, radiation, viruses or, in animal models, by transgenic oncogenes or Helicobacter hepaticus. Different types of FAH have been distinguished and related to three main preneoplastic hepatocellular lineages: (1) the glycogenotic-basophilic cell lineage, (2) its xenomorphic-tigroid cell variant, and (3) the amphophilic-basophilic cell lineage. The predominant glycogenotic-basophilic and tigroid cell lineages develop especially after exposure to DNA-reactive chemicals, radiation, hepadnaviridae, transgenic oncogenes and local hyperinsulinism, their phenotype indicating initiation by insulin or insulinomimetic effects of the oncogenic agents. In contrast, the amphophilic cell lineage of hepatocarcinogenesis has been observed mainly after exposure of rodents to peroxisome proliferators that are not directly DNA-reactive or to hepadnaviridae, the biochemical pattern mimicking an effect of thyroid hormone, including mitochondrial proliferation and activation of mitochondrial enzymes. Hepatic preneoplastic lesions are increasingly used as end-points in carcinogenicity testing, particularly in medium-term carcinogenesis bioassays. This has been complemented more recently by the use of FAH as indicators of chemoprevention, although possible pitfalls of this approach have to be considered carefully. Our ever-increasing knowledge on the metabolic and molecular changes that characterize preneoplastic lesions and their progression to neoplasia provides a new basis for rational approaches to chemoprevention by drugs, hormones or components of the diet.

Introduction

Hepatocellular carcinoma (HCC) is one of the most frequent malignant neoplasms in humans, and has a very poor prognosis. Primary and secondary prevention appear to be the most promising approaches in the fight against this fatal disease. Chronic infection with the hepatitis B (HBV) and C (HCV) viruses, ingestion of foodstuffs contaminated with chemical hepatocarcinogens, particularly the naturally occuring mycotoxin aflatoxin B₁, and abuse of alcoholic beverages have been identified as major risk factors for the development of HCC (Bosch, 1997; Montesano et al., 1997; Stuver, 1998). At least some of these factors may act synergistically, as suggested particularly for HBV and aflatoxins by epidemiological observations. Vaccination against HBV has been introduced in several high-risk areas for HCC and the first results are promising (Chang et al., 1997). However little, if any, progress has been made in prevention of HCC due to other risk factors.

For most of the risk factors for human HCC, appropriate animal models, including chronic infection of woodchucks with the woodchuck hepatitis virus (WHV) which is closely related to HBV, have been established (Okuda & Tabor, 1997). These models were instrumental in the analysis of the mechanism of hepatocarcinogenesis, and especially that of hepatic preneoplasia (Bannasch, 1996). Preneoplastic foci of altered hepatocytes (FAH) precede the manifestation of both benign (adenoma) and malignant hepatocellular neoplasms by long lag periods, which may vary between months and years depending on the...
cause of neoplastic development and the life span of the species affected. FAH were discovered more than three decades ago in rodents treated with nitrosamines (Bannasch, 1968; Friedrich-Freksa et al., 1969) and have since been observed in a large number of species, including non-human primates and humans, after exposure to hepatocarcinogenic agents of virtually all known classes, such as various chemicals, hormones, HBV, HCV, WHV, Helicobacter hepaticus and radiation with X-rays, neutrons or α-particles from Thorotrast. FAH have also been found in transgenic iodent strains and a mutant (LEC) rat strain suffering from hereditary hepatitis, which are prone to develop a high incidence of HCC (Grisham, 1996; Bannasch & Schröder, 2001). FAH have been studied most extensively in rodent models of chemical hepatocarcinogenesis (Grisham, 1996; Bannasch & Schröder, 2001). FAH have been used most extensively as endpoints in carcinogenicity testing (Bannasch, 1986; US National Institute of Environmental Health Sciences, 1989), particularly in risk identification by medium-term carcinogenesis bioassays (Ito et al., 1998; Williams & Enzmann, 1998). More recently, FAH have also been used as biomarkers for studying chemopreventive effects in experimental hepatocarcinogenesis. Although this approach appears to be attractive, it is evident that only detailed knowledge of the pathobiology of the preneoplastic lesions and of the various animal models of hepatocarcinogenesis employed can avoid pitfalls in the evaluation of possible chemopreventive effects.

Pathomorphology of preneoplastic hepatocellular lineages
Experimental chemical hepatocarcinogenesis
For a long time, hepatic preneoplasia as defined above was almost exclusively studied during experimental hepatocarcinogenesis in rodents. On the basis of cytomorphological and simple cytochemical criteria, resulting mainly from staining of alcohol-fixed serial sections with haematoxylin and eosin (H&E) and the periodic acid–Schiff reaction (PAS) to reveal glycogen, at least eight different types of preneoplastic FAH have been distinguished (Bannasch & Zerban, 1992; Goodman et al., 1994). Comprehensive sequential morphological, stereological and biochemical studies in situ revealed that the different phenotypes of FAH are integral parts of preneoplastic hepatocellular lineages leading from highly differentiated hepatocellular phenotypes to poorly differentiated neoplastic phenotypes. Three main hepatocellular lineages have been distinguished (Figure 1): (1) the glycogenotic-basophilic, (2) the xenomorphic-basophilic, and (3) the glycogenotic-acidophilic.
Figure 1. Schematic diagram of hepatocellular lineages emerging in rodent liver during hepatocarcinogenesis.
The predominant sequence of cellular changes (centre) starts with glycogenotic clear and acidophilic (smooth endoplasmic reticulum-rich) hepatocytes and progresses through intermediate phenotypes in mixed cell populations to glycogen-poor, homogeneously basophilic (ribosome-rich) cellular phenotypes prevailing in undifferentiated hepatocellular carcinomas. The tigroid basophilic cell lineage (to the right), originating from xenomorphic hepatocytes (X-cells), is characterized by cells with abundant highly ordered stacks of the rough endoplasmic reticulum and apparently represents a less altered variant of the glycogenotic-basophilic cell lineage. The amphophilic cell lineage (to the left), which has hitherto been described mainly in rats treated with nongenotoxic peroxisome proliferators, and may include oncocytes in woodchucks chronically infected with the woodchuck hepatitis virus, consists of cells with a glycogen-poor cytoplasm containing both abundant granular-acidophilic (mitochondria and peroxisomes) and basophilic (ribosomes) components (from Bannasch, 1998).
tigroid, and (3) the amphophilic-basophilic cell lineage (Bannasch, 1996). After exposure of rats to the majority of hepatocarcinogenic chemicals, especially DNA-reactive compounds, the glyco-
genotic-basophilic lineage prevails. The sequence of cellular changes in this lineage starts with the appearance of glycogenotic clear and acidophilic cell foci and passes through mixed cell populations before formation of glycogen-poor, basophilic (ribosome-rich) neoplastic lesions. This progression-linked phenotypic instability is associated with a gradual reduction of the glycogen initially stored in excess, a multiplication of ribosomes resulting in increased cytoplasmic basophilia, and an ever-increasing cell proliferation and expansion from small to large foci (Bannasch, 1968; Moore & Kitagawa, 1991; Bannasch & Zerban, 1997). Although a minor but significant increase of cell proliferation is seen in the earliest glycogenotic foci, there is an inverse relationship between the gradual reduction of glycogen and the pronounced increase in cell proliferation during neoplastic development at later time points (Zerban et al., 1994). The xenomorphic-tigroid cell lineage represents a less altered variant of the glycogenotic-basophilic cell lineage (Weber & Bannasch, 1994c; Ströbel et al., 1998).

In contrast, the amphophilic cell lineage is characterized by a completely different phenotype, frequently produced in rat liver by hepatocarcinogens that are not directly DNA-reactive, of the peroxisome proliferator type, including several hypolipidaemic drugs and the adrenal steroid hormone dehydroepiandrosterone (Weber et al., 1988; Metzger et al., 1995). The amphophilic cell foci, synonyms of which are 'atypical eosinophilic foci' (Harada et al., 1989), 'weakly basophilic foci' (Marsman & Popp, 1994), and 'large-cell basophilic foci' (Christensen et al., 1999), are not preceded by glycogenotic foci under most experimental conditions, but are poor in glycogen from the beginning. At the ultrastructural level, the amphophilic cells exhibit a proliferation of mitochondria wrapped by profiles of rough endoplasmic reticulum, and sometimes also an increase in peroxi-
osomes (Metzger et al., 1995). During progression to the malignant phenotype, the number of ribosomes and, consequently, the cytoplasmic basophilia usually increase.

A series of stereological studies based on the morphological classification of FAH confirmed the progression-linked phenotypic instability of the predominant preneoplastic hepatocellular lineage (Table 1), and revealed that the number, size and phenotype of FAH is dose- and time-dependent, correlating with the appearance of hepatocellular adenomas and carcinomas (Moore & Kitagawa, 1986; Enzmann & Bannasch, 1987; Weber & Bannasch, 1994c). The results of these investigations also support previous observations (Moore & Kitagawa, 1986; Farber & Sarma, 1987; Bannasch & Zerban, 1992, 1997) that a reversion-linked phenotypic instability of FAH may occur under certain experimental conditions, especially after repeated but limited administration of high sublethal doses of a single or several carcinogenic chemicals, leading to reappearance of less altered phenotypes after withdrawal of these agents (Weber & Bannasch, 1994a,b,c). The cause of reversion-linked phenotypic instability is poorly understood, but it may be due mainly to the cessation of a proliferative stimulus elicited during carcinogen exposure by severe toxic parenchymal damage.

Experimental physical, viral and hormonal hepatocarcinogenesis

In the past few years, it has been shown that the glycogenotic-basophilic and tigroid-xenomorphic lineages develop not only in experimental hepatocarcinogenesis induced by chemicals such as nitrosamines, aflatoxin B1 and phenobarbital, but also in animal models of physical, viral and hormonal hepatocarcinogenesis (Table 2). In addition to neutrons and α-particles from Thorotrast (Ober et al., 1994), X-rays have been reported to produce the glycogenotic-basophilic cell lineage (Oehlert, 1978). Particularly rewarding for the understanding of human hepatocarcino-
genesis are the findings in the woodchuck model of hepatadnaviral hepatocarcinogenesis (Toshkov et al., 1990; Radaeva et al., 2000) and in the transgenically established mouse models established by Chisari (Toshkov et al., 1994) and Kim et al. (1991), in which subgenomic fragments of HBV, coding for the large envelope polypeptide and the X protein, respectively, are expressed and trigger the development of hepatocellular carcinomas.
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Table 1. Chemical hepatocarcinogenesis: characteristics of preneoplastic cellular changes

- **Early emergence** of foci of altered hepatocytes (FAH) in all models of chemical hepatocarcinogenesis
- **Phenotypic diversity and instability**
  - Integration of certain types of FAH in **three main hepatocellular lineages**
  - **Dose- and time-dependence** of number, size, and phenotype of FAH correlates with appearance of hepatocellular neoplasms
  - **Progression-linked phenotype instability** is associated with ever-increasing cell proliferation (and apoptosis) and FAH expansion
  - **Reversion-linked phenotypic instability** results in reappearance of early preneoplastic phenotypes but not in normal liver parenchyma
- **Lack of consistent genotypic changes** in FAH
- **Field effects** rather than repeated clonal selections characterize progression of FAH
- **Mathematical modelling** of phenotypic cellular changes as epigenetic events

Table 2. Hepatocellular lineages in animal models of hepatocarcinogenesis

**Glycogenotic-basophilic/xenomorphic-tigroid cell lineages**
- **Chemicals**: nitrosamines, aflatoxin B1, thioacetamide, phenobarbital
- **Radiation**: X-rays, neutrons, α-particles of Thorotrast
- **Viruses**: woodchuck hepatitis virus, subgenomic fragments of hepatitis B virus and simian virus 40
- **Insulin**: intrahepatic transplantation of pancreatic islets in diabetic rats

**Amphophilic-basophilic cell lineage**
- **Chemicals**: peroxisome proliferators including dehydroepiandrosterone
- **Virus**: woodchuck hepatitis virus

The amphophilic-basophilic cell lineage has also been observed in experimental chemical, hormonal and hepadnaviral hepatocarcinogenesis (Bannasch et al., 1995; Metzger et al., 1995; Dombrowski et al., 2000; Radaeva et al., 2000). However, while the glycogenotic-basophilic and amphophilic-basophilic cell lineages are produced by different types of chemicals in the rat, they frequently coexist in hepadnaviral hepatocarcinogenesis in woodchucks.

**Human hepatocarcinogenesis**
In resected livers from humans suffering from liver cell cancer and cirrhosis as a consequence of a variety of chronic liver diseases predisposing to HCC (Table 3), FAH comparable to those observed in
animal models are often found (Altmann, 1994; Bannasch, 1996). We have evidence for the pre-neoplastic nature of the glycogenotic-basophilic cell lineage (Bannasch et al., 1997b; Su et al., 1997), but this remains to be demonstrated for the amphophilic cell population in human hepatocarcinogenesis. Cases of inborn hepatic glycogenosis, which result from a genetically fixed defect of glucose-6-phosphatase and are associated with a high risk of developing hepatocellular neoplasms when the patients pass through adolescence, seem to be of particular heuristic value (Bannasch et al., 1984; Bianchi, 1993).

**Pathobiology of preneoplastic hepatocellular lineages**

The abnormal morphology of FAH is associated with a variety of biochemical and molecular aberrations, as demonstrated by cytochemical, microbiological and molecular biological methods (Moore & Kitagawa, 1986; Farber & Sarma, 1987; Schwarz et al., 1989; Pitot, 1990; Farber, 1996; Bannasch et al., 1997a; Mayer et al., 1998a; Feo et al., 2000a). Aberrations in energy and drug metabolism have attracted the most attention, but other metabolic pathways may also be affected. Resistance to experimentally induced haemochromatosis was introduced as a marker of various types of FAH (including glycogen storage foci) in rodents (Williams et al., 1976) and has been successfully applied to the detection of FAH in human hereditary haemochromatosis (Deugnier et al., 1993). Similarly, excessive storage of glycogen (glycogenosis) and reduced activity of glucose-6-phosphatase, which were the first biochemical markers of FAH discovered in rodents (Bannasch, 1968; Friedrich-Freksa et al., 1969), have been valuable for the identification of corresponding focal lesions in human liver (Bannasch et al., 1997b). Among the enzymes involved in drug metabolism, γ-glutamyltranspeptidase (γGT) (Kalengayi et al., 1975) and the placental form of glutathione S-transferase (GSTP) (Sato et al., 1984) have been widely used as markers for FAH (Sato, 1989). It is important to realize, however, that the three preneoplastic hepatic cellular lineages differ fundamentally in not only their morphological but also their biochemical phenotype. Thus, while γGT and GST-P are reasonable markers for FAH of the glycogenotic-basophilic cell lineage, they fail to reveal the majority of tigroid cell foci (Ströbel et al., 1998), and are completely absent from amphophilic cell foci (Rao et al., 1982; Mayer et al., 1998a). Changes in the expression of certain genes, including those coding for various growth factors, and molecular genetic alterations, most of which were not studied in specific types of FAH and showed considerable interspecies variations, are considered by Grisham (1996), Bannasch & Schröder (2001) and Feo et al. (2000a).

We have studied the biochemical phenotype of the two main preneoplastic hepatic cellular lineages, the glycogenotic-basophilic and the amphophilic-basophilic lineages, using the nitrosamine-induced stop model of rat hepatocarcinogenesis (Bannasch, 1968) and rat liver continuously exposed to dehydroepiandrosterone (Metzger et al., 1995; Mayer et al., 1998a). The preneoplastic FAH occupy a maximum of 10% of the total liver volume, precluding the application of conventional biochemical or molecular biological approaches in tissue homogenates. We have, therefore, adopted enzyme histochemical, immunohistochemical, microbiological and molecular biological methods in situ (Bannasch et al., 1984, 1997a). Based on these approaches, metabolic and molecular patterns in the predominant types of preneoplastic hepatic foci have been outlined.

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**Table 3. Hepatocellular lineages in human hepatocarcinogenesis**

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<tr>
<th>Glycogenotic-basophilic cell lineage</th>
<th>Amphophilic cell populations</th>
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<tr>
<td>• HCC-bearing livers with and without cirrhosis</td>
<td>• Frequent appearance under similar conditions, except inborn hepatic glycogenosis</td>
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<td>• Posthepatic cirrhosis (hepatitis B virus or hepatitis C virus)</td>
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<tr>
<td>• Alcoholic cirrhosis</td>
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<tr>
<td>• Biliary cirrhosis</td>
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<td>• Cryptogenic cirrhosis</td>
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<td>• Inborn hepatic glycogenosis</td>
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Phenotypes mimicking a response to insulin

In the glycogenotic foci, several metabolic changes apparently act in concert favouring glycogen accumulation (Bannasch et al., 1997a; Mayer et al., 1998b). In addition to inactivation of the adenylate cyclase-mediated signalling pathway, resulting in disturbance of phosphorylytic glycogen breakdown, the hydrolytic lysosomal degradation of glycogen by α-glucosidase is reduced. Decreased activity of glucose-6-phosphatase and expression of the glucose transporter protein GLUT2 indicate a downregulation of gluconeogenesis (Grobholz et al., 1993). In contrast, increased activities of the key enzymes pyruvate kinase and glucose-6-phosphate dehydrogenase point to upregulation of glycolysis and the pentose phosphate pathway, providing precursors and energy for nucleic acid synthesis associated with increased cell proliferation (Hacker et al., 1982, 1998; Klimek et al., 1984). This metabolic pattern is consistent with an insulinomimetic effect of the oncogenic agents (Klimek & Bannasch, 1993; Bannasch et al., 1997a). Direct evidence for such an effect in the early stages of hepatocarcinogenesis has been provided by a new animal model of hormonal hepatocarcinogenesis. Low-number intraportal pancreatic islet transplantation in streptozotocin-diabetic rats results in rapid development of proliferative focal lesions, the morphological and biochemical phenotype of which is similar to that induced by a variety of oncogenic agents (Dombrowski et al., 1994, 1997). Within 1–2 years, the early-emerging glycogenotic foci gradually undergo metamorphosis towards a glycogen-poor, basophilic phenotype and give rise to hepatocellular adenomas and carcinomas, which regularly contain pancreatic islet cells. It may be relevant that an excess risk of primary liver cancer in human patients with diabetes mellitus has been repeatedly reported (Adami et al., 1996; Moore et al., 1998; Stuver, 1998); implications of the hyperinsulinaemia–diabetes–cancer link for preventive efforts have been considered (Moore et al., 1998).

These observations and considerations prompted us to investigate the expression of several components of the insulin signalling cascade (Figure 2) in FAH that emerge in the stop model of chemical hepatocarcinogenesis. We chose to study the insulin-receptor (IR), the receptor of the insulin-like growth factor I (IGF-RI), the insulin receptor substrates-1 and -2 (IRS-1, IRS-2) and the mitogen-activated extracellular signal-regulated kinase-1 (MEK-1) by immunohistochemistry (Nehrbass et al., 1998, 1999; Nehrbass, 2000), and the proto-oncogenes c-raf-kinase and c-myc by in situ hybridization (Bannasch, 1996). The proto-oncogene c-raf holds a central position in several intracellular signalling cascades (Slupsy et al., 1998). The product of the c-myc proto-oncogene acts as a transcription factor that, according to studies in transgenic mice, regulates hepatic glycolysis (Valera et al., 1995). In early glycogenotic foci, all components of the insulin signalling cascade studied were upregulated, as demonstrated particularly convincingly for IRS-1, which is a multi-site docking protein acting as a principal intracellular substrate of the insulin receptor tyrosine kinase (Table 4). These findings suggest that activation of the insulin-stimulated raf-MAP kinase signal transduction pathway elicits preneoplastic hepatic glycogenesis (Nehrbass et al., 1998, 1999).

In hepadnaviral hepatocarcinogenesis, the insulinomimetic effect may also be responsible for the downregulation of expression of the viral surface antigen in glycogenotic FAH, as observed in HBV infected woodchucks (Bannasch et al., 1995; Radaeva et al., 2000) and human HBV carriers (Su et al., 1998), since it has been shown in studies on a human hepatoma cell line that insulin may indeed suppress the expression of the surface antigen (Chou et al., 1989). In situ investigations on the glycogenotic-basophilic cell lineage of human hepatocarcinogenesis have revealed that in HBV carriers, preneoplastic FAH of any type preferentially albeit rarely express the X protein of HBV, while p53 accumulation is invariably negative in FAH but correlates with neoplastic progression in HCC, irrespective of the risk factors involved in regions with low exposure to aflatoxins (Su et al., 1998, 2000).

Progression-linked downregulation of insulin signalling during cellular dedifferentiation

As previously shown in experimental chemical hepatocarcinogenesis for the c-raf-kinase (Bannasch, 1996), the overexpression of most of the proteins of the insulin signalling cascade studied in the early glycogenotic cell populations presenting a high grade of differentiation is only...
Figure 2. Selected signal transduction pathways involved in hepatocarcinogenesis, particularly the insulin-stimulated ras-, raf-, mitogen-activated signalling cascade (centre) and the glucagon-stimulated, adenylate cyclase-mediated pathway (to the left).

AC, adenylate cyclase; GRB2, growth factor receptor binding protein-2; GSK-3, glycogen synthase kinase-3; ins, insulin; IGF-I, insulin-like growth factor-I; IGF-II, insulin-like growth factor-II; IGF-IR, insulin-like growth factor-I receptor; IR, insulin receptor; IRS-1/2, insulin receptor substrate-1 and -2; MAPK, mitogen-activated protein kinase; MEK, mitogen-activated extracellular signal-regulated kinase; PDK1, phosphoinositide-dependent protein kinase-1; P13K, phosphatidylinositol-3-kinase; PKA, protein kinase A; PKB (=Akt), protein kinase B; PP1, protein phosphatase 1; mSOS, mammalian son of sevenless; pY, phosphotyrosine.
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Insulinominetic effect elicits preneoplastic glycogenotic phenotype

- Activation of insulin-signalling pathway: e.g. overexpression of insulin receptor, insulin-growth factor-I receptor, insulin receptor substrate-1, insulin receptor substrate-2, mitogen-activated extracellular signal-regulated kinase-1, and c-ras; increased synthesis of glycogen and/or fat; reduced activities of glucose-6-phosphatase and α-glucosidase; increased activity of glucose-6-phosphate dehydrogenase and cell proliferation

- Inactivation of glucagon-signalling pathway: e.g. reduced activities of adenylate cyclase and glycogen phosphorylase; increased liver type pyruvate kinase activity

Progression from preneoplastic glycogenotic to neoplastic basophilic phenotype

- Downregulation of insulin-signalling pathway

- Isoenzyme shift (e.g. glucokinase/hexokinase; liver type pyruvate kinase/fetal pyruvate kinase) stimulating glycolysis

- Further increase in pentose phosphate pathway (glucose-6-phosphate dehydrogenase) and cell proliferation

- Gradual reduction of gluconeogenesis and glycogenesis

Table 4. Hormone-like effects of hepatocarcinogenic agents – I

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transient, and is gradually downregulated during progression-linked dedifferentiation in later stages of hepatocarcinogenesis (Nehrbass et al., 1998, 1999; Nehrbass, 2000). This event is closely related to the reduction in the glycogen initially stored in excess (Table 4), a further increase in the expression and activity of the key enzyme of the pentose phosphate pathway, elevation of cytoplasmic basophilia due to an increase in the number of ribosomes, and an ever-increasing cell proliferation and expression of c-myc (Bannasch, 1996; Bannasch et al., 1997a). At about the same time, a shift from adult to fetal glycolytic isoenzymes, for example from glucokinase to hexokinase, and the liver-specific L-pyruvate kinase to the fetal M₂-pyruvate kinase takes place (Klimek & Bannasch, 1990, 1993; Hacker et al., 1998; Steinberg et al., 1999). In addition, the fetal glucose transporter protein GLUT1 emerges, while the earlier downregulation of the liver-specific adult glucose transporter protein GLUT2 is maintained (Grobholz et al., 1993). This pronounced shift from anabolic to catabolic glucose metabolism is probably a prerequisite for a more effective energy supply favouring the increase in cell proliferation. It remains to be clarified, however, by which growth factors cell proliferation is further stimulated when the insulin signalling pathway is downregulated. We have speculated that the relatively weak early proliferative stimulus mediated by insulin may be replaced by alternative growth factors (Nehrbass et al., 1998), particularly IGF-II, which has been shown to be frequently overexpressed in late stages of hepatocarcinogenesis (Rogler et al., 1995). Growth stimulation by IGF-II is preferentially or exclusively mediated by pathways that have not been completely clarified, but may stimulate cell proliferation without exerting insulinomimetic effects on glycogen metabolism.

Phenotypes mimicking responses to thyroid and ovarian hormones

In contrast to the glycogenotic foci, the preneoplastic amphophilic cell foci induced in rats by the peroxisome proliferator dehydroepiandrosterone are characterized by downregulation of IRS-1 and show a completely different histochemical pattern (Weber et al., 1988; Mayer et al., 1998a; Nehrbass et
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al., 1999). Whereas a reduction in the activity of enzymes of glycogen metabolism is associated with an early loss of glycogen, the gluconeogenic enzyme glucose-6-phosphatase, several mitochondrial enzymes including cytochrome c oxidase and glyceraldehyde-3-phosphate dehydrogenase, and some peroxisomal enzymes are usually increased in their amount or activity (Table 5), suggesting a thyromimetic effect of dehydroepiandrosterone and other peroxisome proliferators (Bannasch et al., 1997a; Mayer et al., 1998a). A thyromimetic action of several peroxisome proliferators such as clofibrate and acetylsalicylic acid on rat liver, including changes in messenger RNA levels of certain genes involved in mitochondrial biogenesis has been reported (Cai et al., 1996). In addition, a thyromimetic effect of peroxisome proliferators on the activities of several enzymes such as glyceraldehyde-3-phosphate dehydrogenase, malic enzyme and glucose-6-phosphatase has been found in rat liver homogenates and cultured hepatocytes (Hertz et al., 1993, 1996).

In rodents, a number of the biological actions of peroxisome proliferators including dehydroepiandrosterone have been shown to be mediated by the peroxisome proliferator-activated receptor α (PPARα), a member of the superfamily of nuclear steroid receptors (Green & Wahli, 1994; Schoongans et al., 1997), which also mediate effects (possibly including peroxisome proliferation) of the thyroid hormone T3 (Francavilla et al., 1994; Ledda-Columbano et al., 1999). PPARα is apparently responsible for peroxisome proliferation, activation of target genes encoding fatty acid-metabolizing enzymes, mitogenesis and ultimately hepatocarcinogenesis (Gonzalez et al., 1998). In contrast to wild-type mice, PPARα-null mice that were treated with a potent peroxisome proliferator developed neither hepatocellular neoplasms nor preneoplastic hepatocellular foci (Peters et al., 1997). PPARα is also required for gene induction by the less potent peroxisome proliferator dehydroepiandrosterone in mice (Peters et al., 1996). However, according to Hertz and Bar-Tana (1998), the biological effects exerted by peroxisome proliferators in the human liver may be mediated by transduction pathways independent of PPARα.

In the rat, the hypothesis of a thyromimetic effect of peroxisome proliferators eliciting the amphiophilic preneoplastic phenotype has been substantiated by the recent observation of focal hyperproliferative hepatic lesions with a similar morphological and biochemical phenotype after intrahepatic thyroid tissue transplantation in thyroidectomized animals (Dombrowski et al., 2000). Labelling of these rapidly emerging lesions with bromodeoxyuridine showed considerable proliferation within the transplants and in the surrounding amphiophilic cell populations. Eighteen months after thyroid tissue transplantation, large amphiophilic lesions were found, but frank hepatocellular neoplasms were not observed in this animal model. Hyperproliferative focal lesions resembling in some respects amphiophilic cell foci were also induced in rat liver by intraportal transplantation of ovarian tissue in ovariec-tomized rats (Klotz et al., 2000). In a preliminary long-term experiment, four of six animals developed hepa-

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**Table 5. Hormone-like effects of hepatocarcinogenic agents - II**

**Thyromimetic effect elicits preneoplastic amphiophilic phenotype**

- Downregulation of component (insulin receptor substrate-1) of insulin-signalling pathway
- Increased activity of glucose-6-phosphatase and glycogen loss
- Mitochondrial proliferation
- Increase in mitochondrial enzymes (glycerol-3-phosphate dehydrogenase, succinate dehydrogenase, cytochrome c oxidase) and malic enzyme
cellular neoplasms including three HCC, the phenotype of which was similar to that of the amphophilic-like FAH.

Although the glycogenotic and the amphophilic cell lineages are very different at first glance, there is circumstantial evidence from some experiments that they may transform into each other (Bannasch et al., 1997a, Mayer et al., 1998a; Radaeva et al., 2000). This interconversion is difficult to understand, but crosstalk between two or several disturbed signal transduction pathways related to insulinomimetic or thyromimetic actions of the oncogenic agents might be involved.

**Hepatic preneoplastic lesions as biomarkers in chemoprevention studies**

**Tissue specificity and phenotypic instability**

The consistent development of preneoplastic FAH in all animal models of hepatocarcinogenesis and their apparent similarity in human hepatocarcinogenesis favour the use of these lesions as biomarkers in chemoprevention studies. A number of compounds such as several antioxidants (Thamavit et al., 1985; Ito et al., 1992) and oltipraz when administered to animals exposed to aflatoxin B1 (Kensler et al., 1987; Roebuck et al., 1991) reduce the formation of both GST-P-positive FAH and HCC in rodents. However, some of the antioxidants (e.g., butylated hydroxyanisole, butylated hydroxytoluene) which inhibit carcinogenesis in the liver may enhance carcinogenesis at other sites (Imaida et al., 1983; Ito et al., 1988), indicating a possible limitation of preventive effects to certain target tissues. In addition, it is evident from the discussion in the preceding sections that preneoplastic FAH are neither uniform nor stable. Their phenotypic instability is an outstanding feature of their biological behaviour, be it related to progression or to reversion of neoplastic development. As discussed previously, the reversion-linked phenotypic instability of FAH may seriously hamper the interpretation of studies on carcinogenesis (Bannasch, 1986; Bannasch & Zerban, 1992). This may be even more critical in chemoprevention studies, since a reduction in the number and size of preneoplastic FAH inherent in the animal model used may be mistaken as a positive chemopreventive effect. Animal models largely avoiding this complication are available (Bannasch & Zerban, 1992, 1997).

The methods applied for identification of preneoplastic FAH in tissue sections are also critical in studies of both carcinogenesis and chemoprevention. Thus, the progression-linked phenotypic instability of FAH characterizing particularly the predominant glycogenotic-basophilic preneoplastic cell lineage implies that certain markers such as the activation of components of the insulin signalling cascade (e.g., IRS-1) are only useful for the detection of early-appearing FAH, while other markers such as cellular hyperproliferation and overexpression of c-myc or M2-pyruvate kinase may only help to detect more advanced types of FAH and hepatocellular adenomas. Several of the standard markers used in many laboratories (e.g., glycogen, glucose-6-phosphate dehydrogenase, GSTP, γGT) are suitable for the demonstration of a large proportion of FAH integrated into the glycogenotic-basophilic cell lineage, but largely or completely fail to show FAH with an amphophilic phenotype (Bannasch & Zerban, 1992, 1997; Mayer et al., 1998a). There is not a single biochemical or molecular marker for all types of FAH. A number of comparative studies have clearly shown, however, that the vast majority of preneoplastic FAH are readily identifiable in H&E-stained tissue sections (complemented by serial sections treated with the PAS reagent in some specific cases) without any additional biochemical marker. The application of H&E-staining may be of particular advantage in chemoprevention studies, since both the morphological and the biochemical phenotype of FAH induced by hepatocarcinogens in a variety of rodent models is often modulated by additional exposure to other chemicals (Bannasch & Zerban, 1997).

**Phenotypic modulation**

In the context of chemoprevention, the phenotypic modulation produced by peroxisome proliferators is of special interest. Several peroxisome proliferators including nafenopin, clofibrate, ciprofibrate and dehydroepiandrosterone inhibit the expression of γGT and GST-P, and cause a rapid loss of glycogen from glycogenotic FAH when given after DNA-reactive hepatocarcinogens (e.g., Numoto et al., 1984; Hosokawa et al., 1989; Gerbracht et al., 1990; Tsuda et al., 1992; Mayer et al., 1998a). Gerbracht et al. (1990) emphasized that there was no increase in apoptosis within FAH
under these conditions, which might have been an alternative explanation for the reduction in the number and size of enzyme-altered foci. After additional administration of clofibrate to rats pretreated with N-nitrosodiethylamine, Hosokawa et al. (1989) found that FAH positive and negative for GST-P could be identified morphologically in H&E-stained sections. The total number of FAH, both positive and negative for GST-P, was higher in rats treated with N-nitrosodiethylamine followed by clofibrate than in those exposed to N-nitrosodiethylamine alone, indicating an enhancing rather than a reducing effect of clofibrate on the development of FAH. A higher incidence of hepatocellular carcinomas was also seen after additional treatment with clofibrate. An enhancing effect of nafenopin on rat hepatocarcinogenesis was found, although preneoplastic FAH were negative for γGT and showed only low levels or absence of several GST isoenzymes (Grasl-Kraupp et al., 1993a,b).

Dehydroepiandrosterone, which had been proposed as a possible chemopreventive agent because it inhibited the focal expression of GST-P in rat liver (Moore et al., 1986; Garcea et al., 1987), later turned out to be a complete hepatocarcinogen of the peroxisome proliferator type (Rao et al., 1992; Hayashi et al., 1994; Metzger et al., 1995) and to enhance carcinogenesis in the liver (Metzger et al., 1998) as well as in several other tissues (Feo et al., 2000b). In Fischer-344 rats initiated with a single dose of N-nitrosodiethylamine, feeding a diet supplemented by the thyroid hormone T₃ led to a 70% reduction in the number of GST-P-positive FAH per cm², although this hormone exerts strong mitogenic effects on the liver parenchyma (Ledda-Columbano et al., 1999). This seems to indicate a chemopreventive potential of the thyroid hormone under these experimental conditions despite its mitogenic activity, since the authors found a 50% reduction in the incidence of HCC when similarly pretreated rats were exposed to seven cycles of T₃-supplemented diet, as compared to rats undergoing the pretreatment procedure alone (Ledda-Columbano et al., 2000). Green and black tea, the consumption of which has been shown to be associated with both negative and positive effects on human cancer incidence at various sites (Steele et al., 2000), have been reported to induce hepatic peroxisome proliferation (Bu-Abbas et al., 1999). Thus, it is conceivable that peroxisome proliferators, thyroid hormone and possibly other chemicals may exert both carcinogenic and chemopreventive effects on the liver parenchyma and other target tissues depending on the prevailing biological conditions and the dosing and time schedules employed.

Quantitative assessment of hepatic preneoplasia

The heterogeneity and instability of the phenotypic cellular changes that characterize FAH have serious implications for quantitative assessment (Pitot et al., 1989; Schwarz et al., 1989; Bannasch & Zerban, 1992). Using glycogen retention after starvation as a marker for FAH induced in rat liver by an initiation-promotion protocol, Kaußmann et al. (1985, 1987) estimated that only one carcinoma developed for every 1000 to 10 000 focal lesions that were observed concurrent with the appearance of neoplasms. Although this discrepancy may in part be a consequence of the experimental approach used, the large number of preneoplastic FAH implies a great advantage for the detection of early stages of neoplastic development in diagnostic pathology and interventional approaches for secondary prevention. The observations discussed in this review are not readily compatible with the mathematical standard multistage model of carcinogenesis based on the assumption of repeated clonal selections. Therefore, Kopp-Schneider et al. (1998) have elaborated a new mathematical model of hepatocarcinogenesis called the colour-shift model. In this model, phenotypic changes in focal hepatocellular lesions are treated as epigenetic events, possibly due to alterations in a number of cells from the very beginning, and progressing to hepatocellular carcinomas by changes running parallel in larger cell populations rather than repeated clonal selections as suggested by previous stereological studies on the dose- and time-dependence of the development of FAH in rats exposed to N-nitrosomorpholine (Enzmann & Bannasch, 1987; Weber & Bannasch, 1994a,b,c). Comparative investigations, in which the same morphometric data are being applied to both mathematical models, are under way and should help to further elucidate the sequence of cellular and molecular changes during hepatocarcinogenesis.

Depending on the dose and duration of the carcinogenic treatment, the lag period between the first appearance of FAH and neoplasms may vary
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widely. In N-nitrosomorpholine-treated rats, lag periods for the occurrence of adenomas were between 15 and more than 50 weeks (Weber & Bannasch, 1994 a, b, c). There is at present no established marker which would permit us to predict precisely from the appearance of FAH at what time hepatocellular adenomas and carcinomas will develop. However, for many experimental situations, the assumption of a lag period of 6-42 months (about 15-30% of the average life span of the rat) seems to be reasonable. It is interesting to note that in relation to the average life span, these figures correspond closely to the 15-30 years which pass in the majority of children suffering from inborn hepatic glycogenosis type I until multiple hepatocellular neoplasms occur.

The main shortcoming of preneoplastic FAH for their use in early detection and secondary prevention of human HCC is the small size of the lesions and their location in an organ which is not easily accessible. Thus, most of the early preneoplastic FAH are smaller than a liver lobe, which has an average diameter of 1-2 mm in both rodents and humans. This small size precludes a non-invasive identification by any of the imaging procedures available at present. However, there is some hope that at least certain types of FAH can be diagnosed in patients by fine-needle biopsies. The further elucidation of the molecular and metabolic aberrations associated with neoplastic cell conversion in the liver should eventually provide a rational basis for early diagnosis, chemoprevention and, perhaps, also chemotherapy of HCC.

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References


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