High-Fat, High-Calorie Diet Promotes Early Pancreatic Neoplasia in the Conditional Kras$^{G12D}$ Mouse Model

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Abstract

There is epidemiologic evidence that obesity increases the risk of cancers. Several underlying mechanisms, including inflammation and insulin resistance, are proposed. However, the driving mechanisms in pancreatic cancer are poorly understood. The goal of the present study was to develop a model of diet-induced obesity and pancreatic cancer development in a state-of-the-art mouse model, which resembles important clinical features of human obesity, for example, weight gain and metabolic disturbances. Offspring of Pdx-1-Cre and LSL-KrasG12D mice were allocated to either a high-fat, high-calorie diet (HFCD; ~4,535 kcal/kg; 40% of calories from fats) or control diet (~3,725 kcal/kg; 12% of calories from fats) for 3 months. Compared with control animals, mice fed with the HFCD significantly gained more weight and developed hyperinsulinemia, hyperglycemia, hyperleptinemia, and elevated levels of insulin-like growth factor I (IGF-I). The pancreas of HFCD-fed animals showed robust signs of inflammation with increased numbers of infiltrating inflammatory cells (macrophages and T cells), elevated levels of several cytokines and chemokines, increased stromal fibrosis, and more advanced PanIN lesions. Our results show that a diet high in fats and calories leads to obesity and metabolic disturbances similar to humans and accelerates early pancreatic neoplasia in the conditional KrasG12D mouse model. This model and findings will provide the basis for more robust studies attempting to unravel the mechanisms underlying the cancer-promoting properties of obesity, as well as to evaluate dietary- and chemopreventive strategies targeting obesity-associated pancreatic cancer development.

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Introduction

Pancreatic ductal adenocarcinomas (PaCa) is one of the most lethal human cancers, with overall 5-year survival rate of only 3% to 5% and a median survival period of 4 to 6 months. The incidence of this disease in the United States has increased to more than 45,000 new cases in 2012 and is now the fourth leading cause of cancer mortality in both men and women (1). As the current therapies offer very limited survival benefits, novel therapeutic and preventive strategies are urgently needed to treat this aggressive disease.

It is generally accepted that PaCa arises through the progression of precursor lesions called pancreatic intraepithelial neoplasias (PanIN; refs. 2, 3). Importantly, early-stage PanIN lesions already contain genetic alterations, which are also found in PaCa (4). Essentially, all invasive PaCa contains an activating Kras mutation, which can also be detected in early PanINs (5). These observations led to the stepwise carcinogenesis paradigm, in which Kras mutations are characterized as early, initiating events. This notion is strongly supported by genetically engineered animal models, in which the expression of mutated Kras in PaCa progenitor cells during embryogenesis leads to the faithful recapitulation of PanIN development and stepwise progression (6). However, in this conditional Kras mouse, the development of PaCa occurs late (after ~12 months) and only in few animals (~5% to 10%; ref. 6). Mutated Kras seems to be necessary but not entirely sufficient for the development of invasive PaCa. The presence of another mutation, for example, in the Tp53 or Ink4a/Arf tumor suppressor genes, greatly accelerates PaCa development (7, 8). In addition to its role in cancer initiation, oncogenic Kras is also required for the maintenance of primary and metastatic pancreatic cancer (9). Importantly, besides additional genetic alterations, changes in the pancreatic...
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weight gain and metabolic disturbances. This model would be ideal to unravel underlying mechanism and to evaluate preventive strategies. The importance and feasibility of genetically engineered mouse models for cancer prevention research has been highlighted recently (27–29). We used the conditional KrasG12D mouse model, which was developed by Tuveson and colleagues (6). This model is characterized by the progressive development of PanIN lesions over several months with a low penetration of invasive pancreatic cancer. We hypothesized that the slow development of pancreatic cancers in this model can be accelerated by dietary factors, acting as tumor promoters in KrasG12D-initiated pancreatic cells.

Materials and Methods

Conditional KrasG12D mouse model

To study the effect of a HFCD on pancreatic cancer development, the conditional KrasG12D model from Higori and colleagues was used (6). LSL-KRASG12D and PDX-1-Cre mice were maintained as heterozygous lines. After weaning, offspring of LSL-KRASG12D and PDX-1-Cre mice were fed either a HFCD or a control diet (see below) for 14 weeks. Individually tagged mice had free access to diet and water. Food intake and body weight of each animal were measured twice weekly. After 14 weeks, animals were euthanized, and the entire pancreas and other organs were harvested for further analyses. Animal studies were approved by the Chancellor’s Animal Research Committee of the University of California, Los Angeles (Los Angeles, CA) in accordance with the NIH Guide for the Care and Use of Laboratory Animals.

Experimental diets

The diets were obtained from Dyets, Inc (Table 1). A slightly modified AIN-76A purified rodent diet served as a control diet. Compared with the control diet, our HFCD has increased caloric content (4,536 kcal/kg vs. 3,726 kcal/kg), which stems from an increase in corn oil-based fat content (1,800 kcal/kg vs. 450 kcal/kg). Although approximately 12% of the total calories in the AIN-76A control diet come from fat, about 40% of total caloric intake in the HFCD stems from fat. The corn oil contains about 60% omega-6 polyunsaturated fatty acids (linoleic acid), saturated fatty acids (10.8% palmitic, 2.1% stearic), monounsaturated fatty acids (26.5% oleic), and small amounts of omega-3 polyunsaturated fatty acids (0.6% linolenic). Importantly, the amount of sucrose, salts, and vitamins are kept identical in both diets. To compensate for the increase in corn oil, we reduced the amount of cornstarch in the HFCD accordingly. The diets were handled under low-light conditions, and stored at −20°C. The diets were replaced twice weekly. The stability of the fatty acids in the diets was regularly monitored by the UCLA Nutritional Biomarker and Phytochemistry Core.

Genotyping analysis

Before randomization to the diets, the presence of the KrasG12D and Cre allele was determined by PCR analysis of genomic DNA, as described elsewhere, obtained from ear
biopsies (30). Animals with both the KrasG12D and Cre allele were designated as mutant (KrasG12D/C0), and animals with neither the KrasG12D nor the Cre allele were deemed wild-type (Kras+/C0). At the end of the study at sacrifice, the successful excision-recombination events were confirmed by PCR by the presence of a single LoxP site in the pancreas as described elsewhere (30).

**Metabolic panel**

Serum levels of insulin, insulin-like growth factor-I (IGF-I), glucose, and leptin were measured using the MILLIPLEX MAP Mouse Endocrine Panel (Millipore) according to the manufacturer’s instructions. Briefly, serum samples were obtained, and a dipeptidyl peptidase 4 inhibitor was added to the samples. Standards, controls, and samples were added together with the prepared antibody-immobilized beads to a 96-well Microtiter Filter Plate and incubated on a plate shaker overnight at 4°C. After washing, biotinylated detection antibodies were added and incubated on a plate shaker for one hour at room temperature. Then, streptavidin–phycocerythrin conjugates were added and incubated for an additional 30 minutes. After thorough washing, the plate was read on a Bioplex 200 (Bio-Rad) with Bio-Plex Manager 5.0 software. According to the manufacturer, the assay sensitivity for insulin and all other analytes is 55.6 pmol/L and 6.2 pmol/L, respectively, with an intra- and interassay precision of 3.8% to 10.6% and 4.8% to 20.7%, respectively, a recovery in serum matrix for all analytes of about 100%, and no or negligible antibodies cross-reactivity. For measurements of cholesterol and triglycerides, serum was separated by centrifugation at 5,000 rpm for 10 minutes at room temperature. Serum samples were then stored at −80°C until used in serum chemistry assays. Serum chemistry was obtained by the UCLA Division of Laboratory Animal Medicine.

**Inflammation score**

Full histologic cross-sections of each pancreas were stained with hematoxylin and eosin (H&E) for histopathologic examination by a gastrointestinal pathologist (D.W. Dawson) blinded to treatment conditions. Chronic pancreatitis was graded using a semiquantitative scoring system, as previously described (31), with slight modification. Chronic pancreatitis was given an index score (0–12) reflecting the sum of scores for acinar loss, lobular inflammation, and fibrosis. Acinar loss was based on the percentage loss across the entire cross-section and graded as 0, absent; 1, 1% to 25%; 2, 26% to 50%; 3, 51% to 75%; and 4, more than 75%. Inflammation was based on the average number of lobular inflammatory cells per 40× high-power field (HPF; as counted in 10 nonoverlapping HPFs) and graded as 0, absent; 1, 1 to 30 cells; 2, 31 to 50 cells; 3, 51 to 100 cells; and 4, more than 100 cells. Fibrosis was based on the cumulative area of stromal fibrosis across the entire pancreas and graded as 0, absent; 1, 1% to 5%; 2, 6% to 10%; 3, 11% to 20%; and 4, more than 20% fibrosis.

**Evaluation of PanINs**

Formalin-fixed, paraffin-embedded tissues were sectioned (4 μm) and stained with H&E. Six to eight sections (100 μm apart) of pancreatic tissues were histologically evaluated by a gastrointestinal pathologist blinded to the experimental groups. Murine PanIN lesions (mPanIN) were classified according to histopathologic criteria as recommended elsewhere (32) To quantify the progression of PanIN lesions, the total number of ductal lesions and their grade were determined. Only the highest grade lesion per pancreatic lobule was evaluated. About 100 pancreatic ducts of the entire fixed specimen (head, body, and tail of the pancreas) were analyzed for each animal. The relative proportion of each mPanIN lesion to the overall number of analyzed ducts was recorded for each animal.

**Fibronectin and α-SMA staining in mouse pancreas**

Fibronectin and α-smooth muscle actin (α-SMA) expression, as indicative of stellate cell activation, was evaluated in formalin-fixed mouse pancreatic tissue sections by conventional immunofluorescence techniques. Sections were stained with primary antibodies against fibronectin (F3648) or α-SMA (A2547; both from Sigma-Aldrich) and Alexa Fluor-conjugated secondary antibodies (Life Technologies). Nuclei were counterstained

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**Table 1. Composition of control and experimental diet**

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<tr>
<th></th>
<th>AIN-76A kcal/g</th>
<th>AIN-76A g/kg</th>
<th>HFCD kcal/g</th>
<th>HFCD g/kg</th>
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<td>0</td>
<td>50</td>
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<td>450</td>
<td>9</td>
<td>200</td>
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Results

A diet high in fats and calories leads to obesity and metabolic disturbances in mice

After weaning, offspring of LSL-KRAS$^{G12D}$ × PDX-1-Cre intercrosses (pure C57BL/6 background) were randomly assigned to an AIN-76A–based control diet or a diet rich in fats and calories (HFCD; n = 50 each). Compared with the control diet, our HFCD has increased caloric content (4,536 kcal/kg vs. 3,726 kcal/kg), which stems from an increase in corn oil-based fat content (1,800 kcal/kg vs. 450 kcal/kg). Although approximately 12% of the total calories in the AIN-76A control diet come from fat, about 40% of total caloric intake in the HFCD stems from fat (Table 1). After 14 weeks, mice fed the control diet gained 7.2 ± 2.8 g, whereas mice fed the HFCD increased their body weight by 15.9 ± 3.2 g (Fig. 1A and B; P < 0.05). We did not observe any difference in food consumption between both the groups. In addition, there was no difference in weight gain between female and male mice (Fig. 1C). The development of obesity in HFCD-fed mice was visualized by micro-CT, which showed a marked increase in subcutaneous and visceral fat (Fig. 1D).

To assess whether the increase in body weight was associated with metabolic disturbances, we measured serum levels of insulin, glucose, IGF-I, and leptin. We found that mice fed the HFCD in comparison with control diet-fed animals displayed higher levels of insulin (501 ± 311 pmol/L vs. 223 ± 123 pmol/L; P = 0.047), glucose (305 ± 58 mg/dL vs. 235 ± 71 mg/dL; P = 0.034), IGF-I (8.4 ± 6.5 ng/dL vs. 3.1 ± 1.2 ng/dL; P = 0.048), and leptin (1,375 ± 276 pmol/L vs. 515 ± 243 pmol/L; P < 0.01; Fig. 2). There was no significant difference in serum triglycerides and cholesterol levels between HFCD- and control diet-fed mice (Fig. 2). A separate analysis after genotyping at sacrifice revealed no significant difference in weight gain and metabolic parameters between wild-type (KRAS$^{+/+}$) and mutant mice (KRAS$^{+/G12D}$).

A diet high in fats and calories leads to an inflammatory pancreatic microenvironment in mice

To assess the impact of the HFCD on initiation and maintenance of an inflammatory microenvironment in the pancreas, we histologically evaluated pancreatic tissue sections of mice fed the control and HFCD for the presence of intact acini (and conversely acinar cell loss), number of inflammatory cells, and percentage of stromal fibrosis. As described earlier, each parameter was quantitatively assessed and assigned a score (31). The sum of all individual scores constitutes the pancreatitis index (0–12). Histologic analysis revealed that wild-type mice fed the control diet had essentially no acinar cell loss, negligible inflammatory cell infiltration, and no stromal fibrosis resulting in a pancreatitis index of 0.4 ± 0.5. Wild-type mice fed the HFCD, however, showed minor acinar cell loss, a moderate infiltration of inflammatory cells, and weak stromal fibrosis, resulting in a pancreatitis index of 4.4 ± 1.7 (Fig. 3A and B). Similar to wild-type mice fed the control diet, control diet-fed mutant mice (KRAS$^{+/G12D}$) had minimal loss of...
acinar cells, negligible inflammatory cell infiltration, and weak stromal fibrosis (pancreatic score of 1.3 ± 0.6). Mutant mice fed the HFCD showed more robust signs of pancreatic inflammation with moderate acinar cell loss, inflammatory cell infiltration, and stromal fibrosis, resulting in a pancreatitis score of 6.2 ± 0.8 (Fig. 3A and B). The inflammatory reaction in mutant mice fed the HFCD was similar to HFCD-fed wild-type mice (pancreatitis score of 6.2 ± 0.8 vs. 4.4 ± 1.7). More detailed analyses showed that infiltrating inflammatory cells stained positive for CD3 and F4/80 (Fig. 4), indicating a mixed T cell and macrophage infiltration into the pancreas of HFCD-fed mutant animals. Only very few B220-positive B cells were detected (Fig. 4). Almost no inflammatory cell infiltrates were seen at 14 weeks in mutant mice fed the control diet.

Next, we measured the levels of several cytokines in the pancreas of wild-type and mutant mice fed the control diet or HFCD for 3 months. The HFCD significantly increased the levels of several cytokines and chemokines, for example, eotaxin, G-CSF, MCP-1, and IL-6, were elevated in control diet-fed mutant animals compared with control diet-fed wild-type animals, whereas the HFCD had no significant effect on several cytokine levels in the pancreas of wild-type mice (Fig. 5). We also examined the impact of a HFCD on pancreatic stellate cell activation. Immunofluorescence revealed more robust staining for α-SMA, indicating activated pancreatic stellate cells, in mice fed the HFCD (Fig. 6). This was accompanied by an increased deposition of the extracellular matrix protein fibronectin (Fig. 6).

These studies show that a diet high in fats and calories leads to obesity, metabolic disturbances, and pancreatic inflammation in wild-type and mutant mice.

A diet high in fats and calories accelerates early PanIN development in conditional KrasG12D mice

Next, we sought to determine whether the HFCD accelerates early pancreatic neoplasia. Histologic evaluation of pancreatic tissue sections revealed that after 14 weeks,
mutant mice fed the control diet had mostly normal pancreatic duct morphologies (88.7 ± 2.8%) with scattered mPanIN-1a lesions (10.6 ± 2.8%) and very few mPanIN-1b lesions (0.6 ± 0.3%; Fig. 7A and B). Mutant mice fed the HFCD displayed significantly less normal pancreatic ducts (45.0 ± 1.9%), more mPanIN-1a (43.6 ± 2.3%), mPanIN-1b (7.2 ± 1.3%), mPanIN-2 (2.4 ± 1.1%), and few mPanIN-3 lesions (1.8 ± 0.8%). During the short period of 14 weeks, no invasive pancreatic cancers were seen. Importantly, no pancreatic duct pathologies were seen in wild-type mice fed either the control diet or the HFCD.

Discussion

There is great interest in deciphering the mechanisms by which diet-induced obesity leads to increased risk of developing cancer. Although an association between obesity and cancer is well described, the detailed operative mechanisms are not clearly understood. The purpose of the present study was to develop a model of diet-induced obesity and pancreatic cancer development in a state-of-the-art mouse model, which resembles several important clinical features of human obesity, for example, weight gain and metabolic disturbances. In that context, oncogenic Kras-driven genetically engineered mouse models of pancreatic cancer have been shown to closely mimic the human responses to therapies and have great potential for biomarker discovery and mechanistic studies (33).

As mentioned before, several earlier studies also indicated that high-fat diets enhanced pancreatic carcinogenesis and tumor promotion but did not provide a satisfactory animal model for further mechanistic studies. In particular, mice with a pancreas-specific activation of oncogenic Kras fed a...
high-fat diet showed significantly accelerated PanIN development (26); however, in that study, animals on the high-fat diet did not gain more weight than control animals and remained insulin sensitive, experienced pancreatic exocrine insufficiency with substantial changes in energy metabolism, which together led to an improved glucose tolerance (26). In stark contrast with that report, our results presented here show that conditional KrasG12D mice fed a diet high in fats and calories (i) gained significantly more weight, (ii) experienced metabolic abnormalities with elevated circulating levels of insulin and IGF-I, (iii) did not develop pancreatic exocrine insufficiency, and (iv) showed marked pancreatic tissue inflammation and acceleration of mPanIN development. Clearly, there are substantial differences between the animal models used in the report of Khasawneh and colleagues and the study presented here. It is noteworthy that Khasawneh and colleagues used the p48 promoter to drive pancreas-specific expression of oncogenic Kras in mice on a mixed C57BL/6;129 background, whereas we used mice on a rederived, pure C57BL/6 background, in which pancreas-specific oncogenic Kras is driven by the Pdx-1 promoter (26). Different background strains and promoter constructs may account for the observed differences. This is highlighted by a report emphasizing the importance of strain background on the development of diet-induced obesity, inflammation, and PanINs in genetically engineered mouse models of pancreatic cancer (25).

Our HFCD clearly induced an inflammatory reaction in the pancreas with infiltration of mainly macrophages and
T cells, which was seen in wild-type, as well as mutant mice. This is consistent with other elegant studies, which show prominent infiltration of immune cells with suppressive properties, for example, tumor-associated macrophages, myeloid-derived suppressor cells, and regulatory T cells, during early pancreatic cancer development in genetically engineered mouse models (34, 35). Our analysis of cytokine levels in the pancreas showed a significant elevation of several cytokines and chemokines in the pancreas of mutant animals fed the HFCD. Several CSFs and chemokines were significantly elevated, whereas other major proinflammatory cytokines, for example, IL-1, were not changed after 14 weeks of feeding the HFCD. The importance of CSFs was highlighted in a recent report showing that tumor-derived granulocyte macrophage CSF was necessary and sufficient for recruiting immune-suppressive leukocytes into the pancreas and driving tumor development (36). We also found only a slight elevation of TNF-α in the pancreas of mutant mice fed the HFCD for 14 weeks. These data indicate an early robust stimulation of hematopoietic cell lineages and recruitment of inflammatory cells into the pancreas of mutant animals fed the HFCD. Several CSFs and chemokines were significantly elevated, whereas other major proinflammatory cytokines, for example, IL-1 and TNF-α, produced by the infiltrated immune cells will be highly elevated. Other cytokines, for example, IL-15, which are important for the stimulation and activation of the immune system, were elevated, indicating a complex immune response in the pancreas of mutant mice fed the HFCD. Interestingly, despite a similar histologic picture of pancreatic inflammation in both wild-type and mutant mice fed the HFCD (resulting in a similar pancreatitis index), only mice with the oncogenic Kras mutation showed a marked elevation of several cytokines and chemokines. This indicates a possible re-enforcing crosstalk between the KrasG12D mutation and immune cells in this model.

In our study, only the mutant mice developed mPanIN lesions, indicating that the inflammation alone is not sufficient to initiate pancreatic neoplasia in wild-type C57BL/6 mice. However, compared with control diet-fed animals, the progression of mPanIN lesions in HFCD-fed mutant mouse was significantly accelerated in the presence of an inflammatory tissue microenvironment, suggesting that inflammation can act as a tumor-promoting factor in KrasG12D-initiated cells. There is a thought that high-fat diet-induced tumor promotion is, at least in part, mediated by direct effects of diet-induced hyperlipidemia on initiated cells. Our finding that the HFCD did not lead to elevated serum cholesterol and triglycerides levels argues against a direct effect of diet-induced hyperlipidemia on PanIN progression in this model.

The mechanisms proposed to link obesity to increased cancer risk include the development of insulin resistance leading to compensatory high circulating levels of insulin and IGF-I and inflammation (12, 37). HFCD-induced obesity (with ensuing insulin resistance) is recognized to lead to a chronic, systemic, low-grade inflammatory state with elevations in reactive oxygen species, circulating growth factors, for example, insulin, IGF-I, proinflammatory cytokines, for example, interleukins and leptin, and eicosanoids (12). This inflammatory milieu may be conducive to tumor promotion and is thought to be the major mechanism, by which chronic pancreatitis leads to PaCa (38, 39). Furthermore, a few acute episodes of pancreatitis can also significantly accelerate PanIN development in genetically engineered mouse models of pancreatic cancer (40). Despite the potential clinical importance, studies investigating in detail the mechanisms of diet-induced PaCa in a relevant animal model characterized by obesity and insulin resistance, thereby
mimicking the human condition, have been lacking. Our model and presented results are the first step to unravel the underlying mechanisms.

Taken together, our observations strongly suggest that a diet high in fats and calories, which leads to weight gain and metabolic disturbances, can induce pancreatic inflammation and promote pancreatic neoplasia in the presence of an oncogenic Kras mutation. This model, which recapitulates several important clinical features of human obesity with accompanying weight gain and metabolic disturbances, seems ideal to precisely study the kinetics of several pathophysiological processes during diet-induced pancreatic cancer development and investigate the impact of pharmacologic interventions on this process. Exact insights of diet-induced obesity and cancer growth are of utmost importance for developing preventive and therapeutic interventions and for formulating dietary recommendations.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

References


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