\(\beta\)-Cell Hyperplasia Induced by Hepatic Insulin Resistance

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β-Cell Hyperplasia Induced by Hepatic Insulin Resistance
Role of a Liver-Pancreas Endocrine Axis Through Insulin Receptor A Isoform

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OBJECTIVE—Type 2 diabetes results from a combination of insulin resistance and impaired insulin secretion. To directly address the effects of hepatic insulin resistance in adult animals, we developed an inducible liver-specific insulin receptor knockout mouse (iLIRKO).

RESEARCH DESIGN AND METHODS—Using this approach, we were able to induce variable insulin receptor (IR) deficiency in a tissue-specific manner (liver mosaicism).

RESULTS—iLIRKO mice presented progressive hepatic and extrahepatic insulin resistance without liver dysfunction. Initially, iLIRKO mice displayed hyperinsulinemia and increased β-cell mass, the extent of which was proportional to the deletion of hepatic IR. Our studies of iLIRKO suggest a cause-and-effect relationship between progressive insulin resistance and the fold increase of plasma insulin levels and β-cell mass. Ultimately, the β-cells failed to secrete sufficient insulin, leading to uncontrolled diabetes. We observed that hepatic IGF-1 expression was enhanced in iLIRKO mice, resulting in an increase of circulating IGF-1. Concurrently, the IR-A isoform was upregulated in hyperplastic β-cells of iLIRKO mice and IGF-1-induced proliferation was higher than in the controls. In mouse β-cell lines, IR-A, but not IR-B, conferred a proliferative capacity in response to insulin or IGF-1, providing a potential explanation for the β-cell hyperplasia induced by liver insulin resistance in iLIRKO mice.

CONCLUSIONS—Our studies of iLIRKO mice suggest a liver-pancreas endocrine axis in which IGF-1 functions as a liver-derived growth factor to promote compensatory pancreatic islet hyperplasia through IR-A. Diabetes 58:820–828, 2009

Type 2 diabetes results from a combination of insulin resistance and impaired insulin secretion. Although there is some debate about the primary defect underlying type 2 diabetes, insulin resistance is the most relevant pathophysiological feature of the pre-diabetes state (1,2). Rodent studies have shown that insulin insensitivity in both classic and nonclassic insulin target tissues can play a role in the control of glucose homeostasis (3). Insulin resistance also produces a compensatory increase in insulin secretion generating hyperinsulinemia, and ultimately, it is the failure of the β-cell that causes fasting hyperglycemia and development of type 2 diabetes (1). Several mouse models have been developed to study the contributions of insulin resistance in various tissues to the overall regulation of glucose homeostasis (4). Although total whole-body insulin resistance produced by complete deletion of the insulin receptor (IR) does not produce any major effect on mouse development, these mice die 1 week after birth from severe ketosis (5,6). Combined restoration of IR function in brain, liver, and pancreatic β-cells rescues IR knockout mice from neonatal death, prevents diabetes in a majority of animals, and normalizes adipose tissue content, lifespan, and reproductive function. In contrast, mice with IR expression limited to brain or liver and pancreatic β-cells are rescued from neonatal death but develop lipodystrophic diabetes and die prematurely (7).

Based on studies using tissue-specific conditional knockout of IR, liver, brain, and β-cells represent the key sites of insulin resistance in the development of type 2 diabetes (8–10). The liver-specific IR knockout (LIRKO) revealed that insulin resistance in liver is the most important for development of impaired glucose tolerance and fasting hyperglycemia. In addition, these mice also developed marked β-cell hyperplasia, hyperinsulinemia, and decreased insulin clearance (8). With aging, however, the diabetes in these animals was corrected, suggesting some form of compensatory mechanism possibly linked to the very early onset of insulin resistance in these mice that limited understanding of the full impact of hepatic insulin resistance in the pathogenesis of type 2 diabetes. Moreover, these mice developed liver damage related to appearance of hyperplastic nodules that might have altered glucose production by the liver, leading to regression of the diabetic state with aging (8). To better address the role of adult hepatic insulin resistance in the pathogenesis of type 2 diabetes, we developed an inducible model for generating liver IR deficiency (iLIRKO) in young, weaned mice.

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activation as described previously with minor modifications (12). Animals were housed in virus-free facilities on a 12 h light-dark cycle (on 0700 h, off 1900 h) and were fed with a standard rodent chow ad libitum. All animal experimentation described in this article was conducted in accordance with accepted standards of humane animal use as approved by the corresponding institutional committee.

**Genotyping of the IR**<sup>(loxP/loxP)</sup> **transgenic mice.** IR<sup>(loxP/loxP)</sup> transgenic mice were genotyped by PCR. Tail DNA (100–200 ng) was amplified 30 cycles (40 s, 94°C; 40 s, 60°C; and 1 min, 75°C) by a thermal cyc ler. Two primers flanking the loxP site behind exon four of the IR were used: the forward primer (5'-GATGTCACCCCACTGTCTG-3') and the reverse primer (5'-CT-GATAAGTCTGAGCAGCAG-3'). A 320-bp band was obtained for the floxed allele or a 280-bp band for the wild-type allele.

**Genotyping of the Mx1-Cre transgenic mice.** Mx1-Cre transgenic mice were genotyped by PCR. Tail DNA (100–200 ng) was amplified 35 cycles (1 min, 94°C; 1 min, 60°C; and 1 min, 72°C) on a thermal cycler. To amplify the Mx1-Cre transgene (PCR product, 209 bp), primers SF4 (5'-GCATAACAGCTT- GAAACAGACATGGCTG-3') and SF5 (5'-GCACATGTTACGGGGCCAGGCGG-3') were used.

**Western blot analysis.** Tissues were homogenized as described (11). Western blot analyses of insulin signaling proteins were performed on liver, muscle, brown adipose tissue, and brain homogenates as previously described (13). The antibodies used were anti-IRb (Ab-1) from Oncogene (San Diego, CA), anti-PEPPCK antibody provided by D.K. Granner (Vanderbilt University Medical School, Hannover, Germany), anti-4-fatty acid synthase antibody (purchased from BD Transduction Laboratories, San Diego, CA), and anti-β-actin antibody (Sigma-Aldrich, St. Louis, MO). Anti-IGF-1 antibody was purchased from Upstate Biotechnology (Lake Placid, NY). Anti-phospho-p70-S6-kinase (Thr 421/Ser 424), anti-phospho-p44/p42-MAPK (Thr202/Tyr204), anti-phospho-Akt (Ser 473) antibodies were purchased from Cell Signaling (Beverly, MA). For in vivo insulin signaling studies, mice were injected with 1 unit/kg body wt of human insulin (Novo Nordisk) into the peritoneal cavity. After 10 min, tissues were removed and immediately frozen in liquid nitrogen.

**Histological analysis.** The immunohistochemical analysis of pancreata was performed as described (14). 1-Cell mass was calculated by point-counting morphometric analysis. Relative volumes were calculated for β-cells, non-β-cells, and exocrine tissue. Contaminating tissue (including adipose, lymph nodes, and intestines) was recorded to correct for the pancreatic weight. The β-cell mass was then calculated by multiplying the relative β-cell volume by the corrected pancreatic weight. Staining of liver sections with hematoxylin/eosin, periodic acid Schiff, and Masson reagents was performed using standard techniques. Densitometric analysis was performed using a GS-710 Imaging Densitometer, and signals were quantified using Quantity One software (Bio-Rad Laboratories, Hercules, CA).

**Analytical procedures.** Insulin levels in serum were measured by RIA using mouse insulin as a standard (Linco Research, St. Charles, MO). Radioimmunoassay using mouse IGF-1 as a standard (Diagnostic Systems Laboratories, Webster, TX) measured IGF-1 levels in serum. Glucose tolerance and insulin tolerance tests were performed as previously described (14).

**Results**

**Progressive liver-specific insulin receptor deletion without liver dysfunction.** To create an inducible liver-specific deletion of the IR, IR<sup>(loxP/loxP)</sup> mice (11) were bred with transgenic mice expressing a Cre recombinase transgene under the control of the Mx1 promoter/enhancer. Finally, we obtained mice that all carried two floxed IR alleles and were heterozygous for the Mx1-Cre transgene. Thus, these mice constituted the iLIRKO mouse strain. Given that the deletion of IR varied from ~50–100%, mice were divided into three groups: ones with ~50% of the normal receptor expression, a second group with mice bearing ~25% of normal IR, and a third group containing mice with virtually no remaining IR. Ablation of IR was tissue specific because none of the other insulin target tissues was affected (results not shown). An important feature of the phenotype produced by fetal IR deletion (LIRKO) was the appearance of liver dysfunction and histological changes. However, hematoxylin-eosin staining in liver sections revealed no dysplastic or hyperplastic nodules in 6- and 12-month-old iLIRKO mice as compared with their respective controls. In addition, Masson staining showed no increase in collagen infiltration or fibrosis in iLIRKO mice (Fig. 1, upper panels). Regarding enzymes of hepatic glucose metabolism, postnatal deletion of IR caused a reduction of glucokinase protein expression and a dramatic loss of glycogen liver content in iLIRKO mice consistent with previous observations in the LIRKO model (8). However, the expression of phosphoenolpyruvate carboxykinase or fatty acid synthase genes in 6-month-old mice was unchanged in iLIRKO mice as compared with controls (Fig. 1, lower panels).

**Progressive insulin resistance and glucose intolerance in iLIRKO.** In iLIRKO mice, insulin signaling in vivo is selectively impaired in liver because these mice display normal insulin sensitivity in skeletal muscle (8). At 6 months of age, iLIRKO mice presented defects in insulin signaling, which were proportional to their loss of IR expression. Thus, in the group with 50% reduction in IR expression, there was a marked decrease in Akt, extracellular signal–related kinases (ERKs), and p70S6-kinase activation, whereas in the group with complete IR deletion, insulin was unable to activate these signaling pathways (Fig. 2). Interestingly, although our deletion strategy did not alter the levels of IR expression in other tissues (results not shown), we observed progressive impairment of insulin signaling in some peripheral tissues. Thus, in iLIRKO mice, there was a graded impairment of insulin-stimulated Akt and ERKs signaling in brain, skeletal muscle, or interscapular brown adipose tissue, the degree of which correlated with the severity of IR deletion in the liver (Fig. 2). Similarly, p70S6-kinase signaling was impaired in response to insulin in these tissues and was dependent as well on hepatic IR expression. Insulin signaling in both liver and these extrahepatic tissues was
markedly impaired in 1-year-old iLIRKO mice (results not shown). Our results indicate that the iLIRKO mouse develops primary insulin resistance in the liver, and this is associated with secondary insulin resistance in peripheral tissues, which persists throughout the life of the animal. In conventional LIRKO mice, IR deletion induced severe insulin resistance, which caused glucose intolerance at 2 months of age, but this diabetic phenotype was completely reversed by 6 months of age when these mice presented normal glucose tolerance (8). In contrast, our strategy of deleting the IR after weaning induced progressive insulin resistance in iLIRKO mice from 2 to 6 months old and this persisted at 1 year of age (Fig. 3, upper panels). More importantly, the mice without liver IR displayed progressive glucose intolerance and even developed fasting hyperglycemia at 1 year of age (Fig. 3, lower panels).

Progressive β-cell hyperplasia and failure of insulin secretion with aging. Previously, it was shown that constitutive LIRKO mice developed severe hyperinsulinemia and β-cell hyperplasia by 2 months of age, and this fasting hyperinsulinemia remained unchanged although the glucose intolerance reverted with aging (8). In the present study, iLIRKO presented progressive β-cell hyperplasia as compared with controls. More importantly, the level of hyperplasia was correlated to the level of IR expression in the liver (Fig. 4B). The iLIRKO mice also developed progressive hyperinsulinemia as compared with controls, and this also correlated with the extent of IR deletion in the liver (Fig. 4B). This β-cell expansion persisted throughout life as shown in Fig. 4D. In parallel, plasma insulin increased by 2.5-fold in 1-year-old mice as compared with their controls (Fig. 4D); however, this increase was much lower than at 6 months of age (threefold, Fig. 4D), suggesting a failure of insulin secretion with aging. Additionally, insulin content in pancreas slides of 6-month-old and 1-year-old iLIRKO mice was quantified. The data revealed a 25% increase in the insulin content (P < 0.0001) in 1-year-old as compared with 6-month-old iLIRKO mice (results not shown).

Progressive hepatic expression and plasma concentration of IGF-1 in iLIRKO mice. Previous studies have suggested the presence of a circulating islet growth factor in insulin-resistant states independent of glucose and obesity (21). To address this important issue, we performed Western blot analysis of iLIRKO liver samples using anti–IGF-1 antibodies. We observed increases of IGF-1 expression that depended inversely on the level of IR expression in the liver (Fig. 4A). In parallel, IGFBP1 and IGFBP3 were also upregulated in iLIRKO mice depending on the extent of IR deletion in liver. These data were confirmed in 1-year-old mice (Fig. 4C). Interestingly, iLIRKO mice, which expressed no liver IR,
had significantly increased levels of plasma IGF-1 at 6 months and 1 year of age as compared with controls (Fig. 4A and D, respectively).

**Incorporation of IR-A isoform in pancreatic islets: β-cell lines expressing IR-A, but not IR-B, induce proliferation in response to insulin or IGF-1.** The IR expression in pancreatic islets, as estimated by real-time PCR, significantly increased in iLIRKO mice as compared with controls (Fig. 5A). More importantly, the percentage of IR-A isoform (IR-A) expressed in pancreatic islets dramatically increased in iLIRKO mice as compared with controls (Fig. 5A). To assess whether the balance of IR-A versus IR-B might alter the proliferation rate of islets, we analyzed BrdU incorporation in response to either 10 nmol/l insulin or 10 nmol/l IGF-1 in pancreatic islets of 6-month-old mice. The results demonstrated that IGF-1–induced proliferation was significantly higher in pancreatic islets from iLIRKO mice than in the controls (Fig. 5B). Previous reports suggest that IR-A was twofold more sensitive than IR-B in mediating glycogen synthesis and mitogenesis (22). To further explore these possibilities in mouse β-cells, we generated β-cell lines bearing IR (IRLoxP), lacking IR (IRKO), expressing exclusively IR-A (Rec A), or expressing exclusively IR-B (Rec B) (Fig. 5C). Cell lines expressing IR responded to 10 nmol/l insulin in contrast to cells lacking IR as determined by Western blot analysis of IR phosphorylation (Fig. 5D). Additionally, the four cell lines responded to 10 nmol/l IGF-1 as confirmed by IGF-1R phosphorylation (Fig. 5D). The lack of IR significantly decreased basal glucose uptake in β-cells. Reconstitution with IR-A, but not with IR-B, restored basal glucose uptake to levels higher than those observed in control cells (Fig. 5E). Although both insulin or IGF-1 increased cell viability in control cells, only IGF-1 induced cell viability in β-cells lacking IR. Rec A cells but not Rec B increased cell viability in response to either insulin or IGF-1 (Fig. 5F). When we assessed proliferation by thymidine incorporation, both insulin and IGF-1 increased proliferation in control β-cells, whereas cell lines lacking IR did not respond to IGF-1. Finally, insulin and IGF-1 promoted proliferation in Rec A β-cells but not in Rec B lines (Fig. 5G).

**DISCUSSION**

Insulin promotes both metabolism and growth in the liver. Constitutive ablation of IR in liver causes severe metabolic changes and a reduction of liver size by ~50% (8). Likewise, mice in which there is variable IR deletion (cellular mosaicism) exhibit different degrees of growth retardation and metabolic abnormality depending on the extent of IR deletion. IR ablation in ~80% of cells causes extreme growth retardation and lipoatrophy with β-cell hyperplasia, whereas IR ablation in 98% of cells, although resulting

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**FIG. 2.** Inducible liver-specific insulin receptor knockout (iLIRKO) shows insulin resistance in the liver and extrahepatic tissues. In vivo insulin signaling studies were performed in 6-month-old control and iLIRKO mice. Mice of both experimental groups were injected with 1 unit/kg body wt of human insulin (Novo Nordisk) into the peritoneal cavity. After 10 min of treatment, liver, muscle, BAT (brown adipose tissue), and brain were removed. Protein extracts of these tissues were analyzed by Western blot (WB) with anti-IR antibody from O. ESCRIBANO AND ASSOCIATES. The results are representative of four independent experiments. Histograms summarize the densitometric analysis of the corresponding Western blots.
in similar growth retardation and lipoatrophy, causes diabetes without β-cell hyperplasia (23). These findings suggest that insulin regulates growth independently of metabolism and that the number of insulin receptors is an important determinant of the specificity of insulin action. In the present study, we have used an inducible strategy to generate IR deficiency in liver; thus, we obtained mice with variable levels of IR deletion (liver mosaicism). Based on this iLIRKO model, induction of liver IR deficiency after weaning caused progressive insulin resistance and glucose intolerance without alterations in liver growth. Under our experimental conditions, the effects of insulin on growth and metabolic regulation are mutually independent. Thus, deletion of liver IR in young adults gave rise to irreversible insulin resistance and progressive glucose intolerance, which persisted for up to 1 year, although liver damage was not observed in any iLIRKO mice.

Previous studies with conditional knockouts and reconstitution models concluded that the progression of insulin resistance to diabetes with fasting hyperglycemia requires defects in tissues other than liver (7,8). Moreover, acute deletion of IR in the liver has been reported to impair insulin signaling but does not induce insulin resistance or hyperinsulinemia (24). Our results in iLIRKO mice demonstrated that liver-specific disruption of IR can impair both hepatic and extrahepatic insulin signaling and that the severity of this resistance depends on the extent of IR deletion in the liver. iLIRKO mice display early insulin resistance as a primary defect related directly to the reduction or ablation of liver IR, but they also have impaired insulin signaling in other peripheral tissues, including skeletal muscle and brain. Thus, iLIRKO mice present systemic insulin resistance as a secondary effect. Given that our deletion strategy did not alter IR expression in other tissues, this effect is likely the result of desensitization of the IR in extrahepatic tissues produced by prolonged hyperinsulinemia. Thus, our results demonstrate that a primary defect in the liver triggers secondary insulin resistance in extrahepatic tissues and suggest that the progression to diabetes in iLIRKO mice does not require defects other than liver IR deficiency.

Insulin resistance is associated with hyperinsulinemia and leads to β-cell hyperplasia. Thus, total deletion of liver IR induced β-cell hyperplasia in LIRKO animals (8). However, conditional inactivation of IR in muscle was not associated with either islet hyperplasia or elevated circulating levels of insulin (11). Our results with iLIRKO demonstrate a direct relationship between the level of IR expression remaining in the liver and the fold increase of plasma insulin levels and β-cell mass. Finally, constitutive LIRKO mice displayed dysregulation of insulin secretion for more than 1 year. However, in iLIRKO mice, compensatory hyperinsulinemia in 1-year-old mice was much lower than in 6-month-old mice. Thus, in our model, a failure in insulin secretion by β-cells seems to occur given the inhibition of insulin clearance in the liver, the major site where insulin is degraded in an IR-dependent manner (25). More importantly, the observations from iLIRKO mice are consistent with the idea that IR deletion in the liver triggers secondary insulin resistance in extrahepatic tissues, which is similar to the insulin resistance observed in human diabetes. This study provides a novel model to study insulin resistance and diabetes development.
suggest that owing to severe insulin resistance and prolonged hypersecretion of insulin, the β-cells ultimately undergo a failure to secrete insulin.

Previous evidence demonstrated that insulin signaling is essential for β-cell growth (10,26). Recently, double deficiency for IR in the liver and the β-cells was unable to induce β-cell hyperplasia in response to severe insulin resistance (27). In fact, the persistence of robust hyperplasia in 6-month-old hypoglycemic LIRKO mice supports the concept of a glucose-independent circulating islet growth factor (27). In this context, iLIRKO mice displayed increased liver IGF-1 expression dependent on the extent of IR deletion in the liver. This resulted in a persistent increase of plasma IGF-1, consistent with the fact that the liver is the main source of circulating IGF-1 (28). Previous data demonstrated that conditional deletion of IGF-1R in the β-cell does not alter islet β-cell mass growth, suggesting a role for this receptor in regulating differentiated function (29). Surprisingly, we have found a relationship between hyperinsulinemia and β-cell hyperplasia based on an increase of genes related to β-cell proliferation and differentiation in iLIRKO mice. Thus, IGF-1 signaling might be involved in the induction of genes related to glucose-stimulated insulin secretion, among others. IGFBPs regulate the systemic effects of IGF-1 in a complex manner (30). Interestingly, IGFBP1 was upregulated in parallel to IGF-1 in iLIRKO mice, effects that were dependent on the level of hepatic IR deletion. These results are entirely consistent with the insulin-mediated effect on the IGFBP1 gene expression in liver cells (31). IGFBP1, which is mainly produced by the liver in the adult mice, inhibits IGF-dependent cellular growth in vivo (30,32,33). In addi-
tion, adult transgenic mice showed glucose intolerance and fasting hyperglycemia and hyperinsulinemia. However, the hyperinsulinemia observed in IGFBP1 transgenic mice cannot be attributable to insulin resistance alone (34,35). In fact, adult IGFBP1 transgenic mice displayed larger and more numerous β-cell islets reflecting increased β-cell proliferation (36). The increase of plasma IGF-1 and IGFBP1 in iLIRKO mice contrasts with IGF-1 decreases and IGFBP1 increases in liver-specific Irs1−/−:Irs2−/− mice, a mouse model also showing β-cell mass hyperplasia (37). Finally, the levels of IR were increased in the pancreatic islets of iLIRKO as compared with controls. Moreover, we noted an increase in the expression of IR-A versus IR-B in pancreatic islets from iLIRKO mice. Under our experimental conditions, IGF-1-induced proliferation was significantly higher in pancreatic islets from iLIRKO mice.
mice than in controls. These data strongly support the notion that increased expression of IR-A relative to IR-B may enhance the growth response of pancreatic β-cell to IGF-1. Moreover, based on our observations in mouse β-cell lines, the presence of mostly IR-A in pancreatic islets may cause initially an increase in glucose uptake, a classic mitogenic signal in β-cells (17) and, subsequently, enhanced proliferation in response to either insulin or IGF-1. Alternatively, an increase in IRS-2 in pancreatic islets from iLIRKO mice may account for their enhanced proliferation in response to IGF-1. Our data obtained in pancreatic islets microarrays from iLIRKO versus control mice rule out that possibility (results not shown). Taken all together, our findings imply that IR-A, but not IR-B, confers a proliferative capacity to β-cells, which enables them to respond to insulin or IGF-1; this hypothesis may account for the β-cell hyperplasia induced by liver insulin resistance in iLIRKO mice. Thus, our results in iLIRKO mice seem to suggest a liver-pancreas endocrine axis, whereby increased plasma IGF-1 functions as a liver-derived growth factor to promote compensatory β-cell hyperplasia through IR-A.

In conclusion, our results demonstrate that hepatic IR deficiency can lead to systemic insulin resistance. Given that insulin resistance states can be compensated for by β-cell hyperplasia, studies of iLIRKO emphasize a cause-and-effect relationship between progressive insulin resistance and β-cell hyperplasia. Ultimately, the β-cells fail to secrete sufficient insulin, and this leads to uncontrolled diabetes. Thus, in iLIRKO mice, hepatic insulin resistance is sufficient to recapitulate the progressive pathogenesis of type 2 diabetes. IGF-1 expression was enhanced depending on the extent of hepatic IR deletion, and this resulted in a persistent increase of circulating IGF-1 in iLIRKO mice. Concurrently, IR-A expression was significantly increased in pancreatic islets of iLIRKO mice, presumably providing a mechanism by which the proliferative response to IGF-1 was enhanced in the hyperplastic pancreatic islets of iLIRKO mice. Thus, our studies of iLIRKO mice suggest a liver-pancreas endocrine axis in which IGF-1 functions as a liver factor to promote compensatory β-cell hyperplasia through IR-A.

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No potential conflicts of interest relevant to this study were reported.

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