Lack of glucagon receptor signaling and its implications beyond glucose homeostasis

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Abstract
Glucagon action is transduced by a G protein-coupled receptor located in liver, kidney, intestinal smooth muscle, brain, adipose tissue, heart, pancreatic β-cells, and placenta. Genetically modified animal models have provided important clues about the role of glucagon and its receptor (Gcgr) beyond glucose control. The PubMed database was searched for articles published between 1995 and 2014 using the key terms glucagon, glucagon receptor, signaling, and animal models. Lack of Gcgr signaling has been associated with: i) hypoglycemic pregnancies, altered placentation, poor fetal growth, and increased fetal–neonatal death; ii) pancreatic glucagon cell hyperplasia and hyperglucagonemia; iii) altered body composition, energy state, and protection from diet-induced obesity; iv) impaired hepatocyte survival; v) altered glucose, lipid, and hormonal milieu; vi) altered metabolic response to prolonged fasting and exercise; vii) reduced gastric emptying and increased intestinal length; viii) altered retinal function; and ix) prevention of the development of diabetes in insulin-deficient mice. Similar phenotypic findings were observed in the hepatocyte-specific deletion of Gcgr. Glucagon action has been involved in the modulation of sweet taste responsiveness, inotropic and chronotropic effects in the heart, satiety, glomerular filtration rate, secretion of insulin, cortisol, ghrelin, GH, glucagon, and somatostatin, and hypothalamic signaling to suppress hepatic glucose production. Glucagon (α) cells under certain conditions can transdifferentiate into insulin (β) cells. These findings suggest that glucagon signaling plays an important role in multiple organs. Thus, treatment options designed to block Gcgr activation in diabetics may have implications beyond glucose homeostasis.

Introduction
Glucagon is a 29-amino acid polypeptide secreted by the α or glucagon cell of the islet of Langerhans in response to hypoglycemia, arginine, gastric inhibitory polypeptide (during ambient reduced glucose levels), gastrin, and potassium chloride. Glucagon was initially discovered as a contaminant of pancreatic extracts with glucogenic properties or properties that mobilize glucose in 1923. It took more than 20 years for Sutherland and de Duve to establish that glucagon is secreted by pancreatic α-cells. Between 1959 and 1962, Unger et al. developed a RIA
making it possible to investigate the physiology of glucagon and its role in various disorders (Unger et al. 1959, 1962, Gromada et al. 2007).

As a counter-regulatory hormone, glucagon maintains blood glucose levels by activating glycogenolysis and gluconeogenesis. In addition, glucagon reduces triglyceride, very LDL release, and cholesterol levels and stimulates fatty acid oxidation (Eaton 1973, Longuet et al. 2008). Beyond glucose homeostasis, glucagon elicits significant extra-hepatic effects in tissues such as kidney, heart, adipose tissue (white and brown), gastrointestinal tract, thyroid, and CNS (Lefebvre et al. 1995, Burcelin et al. 1996, Porte et al. 1998, Kieffer & Habener 1999, Kinoshita et al. 2014).

Glucagon action is transduced by a G protein-coupled receptor (GCGR/Gcgr) that is a member of the class II GCGR superfamily of seven transmembrane spanning receptors that are coupled via GTP-binding proteins to adenyl cyclase resulting in an increase in cAMP production. cAMP activates signaling pathways that cause an increase in gluconeogenesis, glycogenolysis, and fatty acid oxidation. In addition, glucagon controls glucose, energy, and lipid metabolism at least in part via AC/cAMP-independent signals including p38MAPK, IP3/DAG/Ca, peroxisome proliferator-activated receptor alpha (PPARα), and fibroblast growth factor 21 (FGF21)-dependent pathways (Berglund et al. 2010, Habegger et al. 2010, 2013, Rodgers 2012, Cyphert et al. 2014).

Binding sites for glucagon have been identified in liver, kidney, intestinal smooth muscle, brain, adipose tissue, heart, pancreatic islet β-cells, and placenta (Ouhilal et al. 2012). Gcgr gene expression is positively regulated by glucagon and negatively regulated by glucagon and agents that increase intracellular cAMP (Quesada et al. 2008).

This review will focus on the role of glucagon and glucagon signaling in fetal growth, pancreatic development, and glucose and lipid homeostasis in genetically modified animal models that have been demonstrated to provide important clues about the role of glucagon in health and disease. Animal models provide an invaluable tool to study the underlying mechanisms associated with glucagon action; however, they have the disadvantage that genetic manipulation could lead to lifelong adaptations that can skew results. Thus, some of the findings may not necessarily translate into human disease.

The PubMed database was searched for articles published between 1995 and 2014 using the key terms glucagon, glucagon receptor, and animal models. Articles obtained from this search are discussed in this review. A brief summary of all the known metabolic changes that have been identified from genetically modified animal models with altered Gcgr expression is provided in Fig. 1.

Role of glucagon on pregnancy maintenance and fetal growth

Disruption of the glucagon receptor gene (Gcgr) during pregnancy is associated with maternal hypoglycemia, hyperglucagonemia, abnormalities of placentation, poor fetal growth, and increased fetal and early postnatal death. Gcgr−/− placentas are characterized by extensive mineralization, fibrinoid necrosis, narrowing of the vascular channels, and a thickened interstitium associated with trophoblast hyperplasia. In addition, lack of glucagon placental signaling down-regulates genes that control growth, adrenergic signaling, vascularization, oxidative stress, and G protein-coupled receptors (Ouhilal et al. 2012).

Role of glucagon in pancreatic development and pancreatic islet morphology

During fetal development, glucagon is required for early insulin or β-cell differentiation and to mature a subset of glucagon cells (Vuguin et al. 2006). In rodent models, disruption of the Gcgr gene is associated with an increase in the number of pancreatic islets and an increase in the number of somatostatin cells without altering insulin cell mass. Lack of glucagon signaling is also associated with a profound glucagon cell hyperplasia. A subset of those glucagon cells coexpress markers of immature islet endocrine cells such as insulin, PDX1, and glucose transporter 2 (Vuguin et al. 2006). Similar to the Gcgr−/− model, glucagon cell expansion is observed in the majority of the models in which there is reduced or absent Gcgr receptor signaling, such as inactivation or a reduction in glucagon and/or its receptor by genetic manipulation, immuno-blockade, or treatment with antisense oligonucleotides (Gelling et al. 2003, Sloop et al. 2004, Conarello et al. 2007, Winzell et al. 2007, Gu et al. 2009, Hayashi et al. 2009, Lee et al. 2011, Longuet et al. 2013). In those studies, α or glucagon cell expansion is accompanied by elevated plasma glucagon levels. One exception has been the study by Liang et al. (2004), which demonstrated that a reduction in Gcgr expression using an antisense oligonucleotide is not accompanied by changes in α or glucagon cell number; however, glucagon levels were nonetheless significantly increased.

Interestingly, specific inactivation of the Gcgr gene in the hepatocyte recapitulates the phenotype observed in
Gcgr<sup>−/−</sup> mice. Specifically, both Gcgr<sup>−/−</sup> mice and the liver-specific Gcgr<sup>−/−</sup> mice have similar reductions in fasting glucose and improved glucose tolerance and insulin sensitivity, and glucagon cell hyperplasia and hyperglucagonemia, suggesting that an independent circulating factor produced by the lack of Gcgr signaling in liver can increase glucagon cell proliferation (Longuet et al. 2013).

**Role of glucagon in food intake and body composition**

Glucagon has beneficial effects on food intake, body fat mass, and energy expenditure (Habegger et al. 2010, Heppner et al. 2010). In addition, glucagon has a satiety effect by decreasing meal size through a combination of peripheral and central actions (Heppner et al. 2010). Consistent with a role in modulating food intake, glucagon also appears to affect the regulation of body weight by promoting weight loss in physiological and pathological doses as observed in patients with glucagonoma (Schulman et al. 1957, Bloom & Polak 1987). In addition, rodent models and in vitro studies have demonstrated that glucagon increases energy expenditure through activation of brown adipose tissue (Billington et al. 1991).

Disruption of the Gcgr gene is associated with a significant decrease in total adipose tissue, which is compensated for by an increase in lean body mass. The changes in body composition are not accompanied by a change in growth rates, food intake, resting O<sub>2</sub> consumption, and energy expenditure when compared with WT.
littermates (Gelling et al. 2003, Vuguin et al. 2006). Notably, during other pathological states, such as insulin deficiency and/or hyperglucagonemia, glucagon increases energy expenditure and thermogenesis. This increase in thermogenesis involves targeting of brown adipose tissue (Yahata & Kuroshima 1987) and white adipose tissue lipolysis (Lefebvre 1975).

When exposed to a high-fat diet, disruption of the Gcgr gene is associated with a decrease in consumption of fat, 30% less weight gain, and protection from high-fat-induced hepatic steatosis when compared with WT littermates (Conarello et al. 2007). In contrast, it has been demonstrated that Gcgr−/− mice have enhanced susceptibility to Jo2-induced liver injury by increasing the apoptotic rate (Sinclair et al. 2008). Moreover, glucagon is essential for hepatocyte survival via regulation of cAMP-dependent pathways that decrease caspase activity (Sinclair et al. 2008).

**Role of glucagon in glucose and lipid homeostasis**

Glucagon plays a central role in the response to hypoglycemia by stimulating gluconeogenesis and glycolysis and opposing the insulin effects. Its main action on the liver is mediated by the activation of adenylyl cyclase and the protein kinase A signaling pathway (Quesada et al. 2008). Glucagon stimulates changes to lower the energy state by activating AMPK signaling in the liver, thereby improving the efficiency by which the liver converts gluconeogenic substrate into glucose following glucagon stimulation (Berglund et al. 2009). The first-line biguanide drug for the treatment of diabetes ‘metformin’ has been shown to antagonize the effect of glucagon in the liver by increasing AMP levels (Miller et al. 2013). Glucagon has also been shown to have an inhibitory effect on insulin secretion. It has been recently shown that glucagon stimulated signaling, via cAMP–PKA–CREB, and the subsequent hepatic production of kisspeptin 1 suppresses insulin secretion (Song et al. 2014). In addition to its effect on the liver, glucagon can suppress hepatic glucose production by acting through the mediodorsal hypothalamic region of the brain, suggesting that glucagon can limit its own direct stimulatory effect in the liver (Migliu et al. 2013).

The lipolytic effect of glucagon in humans has been challenged (Gravholt et al. 2001). In animal models, glucagon has potent hypolipidemic actions (Eaton 1973, Guettet et al. 1991, Bobe et al. 2003). Glucagon decreases triglyceride and very-LDL release by the liver (Guettet et al. 1989, Bobe et al. 2003), reduces plasma cholesterol (Guettet et al. 1988, 1989, 1991), and increases β-oxidation (Prip-Buus et al. 1990). Glucagon action on lipid metabolism is mediated through AMPK-, p38 MAPK-, PPARα-, Foxa2-, and FGF21-dependent mechanisms (Longuet et al. 2008, Berglund et al. 2010, von Meyenn et al. 2013). In addition, glucagon plays a central role in fatty acid oxidation during prolonged fasting and in response to exercise (Longuet et al. 2008, Berglund et al. 2010).

In rodent models, disruption of the Gcgr gene is associated with lower blood glucose levels during the day and the development of hypoglycemia during a prolonged fast, increased plasma LDL, and, in female rodents, decreased levels of triglycerides (Gelling et al. 2003).

**Role of glucagon in the hormonal milieu**

Glucagon does not seem to play an important role in insulin action but induces glucose-stimulated insulin release (Gelling et al. 2003). Similarly, glucagon action stimulates its own secretion in isolated rat and mouse glucagon cells by increasing AMP levels and stimulating somatostatin release (Shimatsu et al. 1983, Ma et al. 2005). In humans, glucagon also has a variety of neuroendocrine effects including the stimulation of GH and cortisol secretion and inhibition of ghrelin secretion (Arafat et al. 2005).

Disruption of the Gcgr gene is associated with hyperglucagonemia and elevated glucagon-like peptide 1 (GLP1) levels, with normal insulin and lactate levels. Gcgr−/− mice have a twofold increase in corticosterone during fasting, low corticosterone levels in the afternoon, and an increased responsiveness to epinephrine when compared with WT littermates. Female Gcgr−/− mice display a small decrease in insulin-like growth factor 1 levels (Gelling et al. 2003). Consumption of a high-fat diet does not alter levels of plasma glucagon, GLP1, triglycerides, non-esterified free fatty acids, or corticosterone in Gcgr−/− mice when compared with WT littermates (Conarello et al. 2007).

**Role of glucagon in satiety and gastric emptying**

Glucagon has been shown to evoke a marked delay in gastric emptying (Jonderko et al. 1989). These anti-motility effects on the gastrointestinal tract (esophagus, stomach, and small and large intestines) are observed when glucagon is administered to humans in pharmacological doses (Patel et al. 1979). Glucagon also controls...
meal size and satiation in both humans and rodents (Geary 1990, Geary et al. 1992).

In rodent models, disruption of the Gcgr gene is associated with decreased gastric emptying (Conarello et al. 2007), increased length of the intestines (by 20%) due to an increased rate of crypt neogenesis and crypt bifurcation, and an increase in the number of L and LK cells/villi compared with WT littermates (Grigoryan et al. 2012).

**Role of glucagon in retinal function**

In rodent models, disruption of the Gcgr gene is associated with a late-onset loss of retinal function, loss of visual acuity, and eventual death of retinal cells (Umino et al. 2006). These retinal changes were observed at 10 months of age and correlated directly with the degree of hypoglycemia.

**Role of glucagon in taste**

Glucagon and its receptor are coexpressed in a subset of mouse taste receptor cells that express T1R3 taste receptor implicated in sweet and/or umami taste (Elson et al. 2010). No major alterations in taste have been described in Gcgr−/− mouse models.

**Role of glucagon in cardiac contractility**

Glucagon exerts positive inotropic and chronotropic effects in the ventricular myocardium by activation of cardiac adenylate cyclase leading to increased cAMP formation (MacLeod et al. 1981, Mery et al. 1990, Gonzalez-Munoz et al. 2008).

In rodent models, disruption of the Gcgr gene is associated with a diminished parasympathetic tone, leading to higher heart rates during the light phase and a modest elevation in the heart rate in response to atropine (Mukharji et al. 2013).

**Role of glucagon in renal blood flow**

Glucagon exerts a positive effect on renal blood flow and glomerular filtration rate, and increases sodium, chloride, potassium, and inorganic phosphorus clearance ratios (Elrick et al. 1958, Baillie et al. 1980, Denis et al. 2003). No major alterations in renal function have been described in Gcgr−/− mouse models.

**Role of glucagon in β (insulin) cell function**

Transgenic mice were engineered to overexpress the Gcgr in insulin cells using the rat insulin II promoter (RIP-Gcgr) to determine the functional role of Gcgr receptor in β-cell function. Overexpression of Gcgr in β-cells increased glucagon-stimulated insulin release and significantly increased β-cell volume, suggesting a role for Gcgr receptor in increased insulin cell competency (Gelling et al. 2009). These data are strengthened by the findings of low levels of PDX1, GLUT2, and MaF, molecules involved in the regulation of insulin expression, in insulin cells of Gcgr−/− mice (Vuguin et al. 2006).

**Role of glucagon in the development of diabetes in insulin-deficient mice**

Elevated glucagon:insulin ratio has been shown to accelerate gluconeogenesis and fatty acid oxidation leading to the formation of ketone bodies (Vons et al. 1991). Hyperglycemia and elevated ketone bodies are the main component of diabetic ketoacidosis (Eledrisi et al. 2006). Disruption of the Gcgr gene in an insulin-deficient diabetic rodent model is accompanied by an asymptomatic, benign, non-catabolic state when followed for 6 weeks (Conarello et al. 2007, Lee et al. 2011), suggesting that ‘other factors’ contribute to the normalization of the catabolic state. Similarly, it has been demonstrated that a low amount of α-cell (2% of the normal α-cell mass) is sufficient to prevent the metabolic dysregulation observed in diabetes (Thorel et al. 2011).

Disruption of the Gcgr gene increases circulating level of FGF21 and GLP1, which promote glucose tolerance independently of insulin level. Thus, FGF21 and GLP1 seem to be the major players in preventing the developing of diabetes in Gcgr−/− diabetic mice (Omar et al. 2014).

**α (glucagon) cell transdifferentiation as a potential treatment for diabetes**

It has been recently demonstrated that, in certain situations, newly formed β-cells can originate from cells that previously expressed glucagon, a phenomenon called transdifferentiation. Such situations include extreme β-cell loss, increased expression of Pax4 in α-cells, forced PDX1 expression, epigenomic manipulation, or the use of the peptide caerulein after treatment with alloxan (Collombat et al. 2009, Liu & Habener 2009, Thorel et al. 2010, Yang et al. 2011, Bramswig et al. 2013, Piran et al. 2014).
Antagonizing glucagon action as a potential treatment for diabetes

If alterations in glucagon secretion are indeed the cause of hyperglycemia and other metabolic complications in diabetic patients, suppression of glucagon signaling can be viewed as an important therapeutic option. Potent peptide antagonists, glucagon-neutralizing antibodies, small-molecule glucagon receptor antagonist, and receptor antisense oligonucleotides have been used in animal models to control hyperglycemia but their use in humans have been limited by their side effects as well as the limited mode of delivery (Johnson et al. 1982, Brand et al. 1994, Qureshi et al. 2004, Estall & Drucker 2006). Recently, four novel peptide-based glucagon analogs have been developed that are resistant to DPP4 degradation and thus display substantial abilities to suppress glucagon action in different animal models (O’Harte et al. 2013). All analogs inhibit glucagon-induced insulin secretion in vitro, and in rodents, analogs inhibited glucagon-induced hyperglycemia and the insulinotropic response (O’Harte et al. 2013).

Conclusion

It has been suggested that, in states of insulin deficiency, excess glucagon secretion plays a major role in the metabolic perturbations associated with diabetes, such as hyperglycemia and ketonuria. Thus, inhibition of glucagon receptor signaling represents a possible option for the treatment of diabetes. Animal models have demonstrated that the physiological processes regulated by glucagon and its receptor are much broader than expected. Glucagon plays important roles in pancreatic development, insulin cell function, and metabolic response to prolonged fasting, exercise, lipid metabolism, hepatic energy state, hepatocyte survival, meal size and satiety, gastric emptying, intestinal length, as well as visual acuity, placenta- tion, and cardiac contractility. In addition, under some extreme metabolic conditions of insulin deficiency, glucagon or α-cells possess the capacity to transdifferentiate into insulin cells. Therefore, antagonizing glucagon action as a therapy for diabetes may improve glucose and insulin levels but in addition may have several unintended consequences that could further compromise the regulatory response to an altered metabolic state.

Declaration of interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of this review.

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