

The Possible Mechanisms for Improvement of Liver Function due to Sodium-Glucose Cotransporter-2 Inhibitors

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To the Editor

Recently, sodium-glucose cotransporter-2 inhibitors (SGLT2is) are frequently used to treat patients with type 2 diabetes. We previously reported that SGLT2is improve liver function in addition to lowering plasma glucose [1, 2]. Hepatic histological improvement by SGLT2is was also observed. SGLT2is reduced scores of steatosis, lobular inflammation, ballooning, and fibrosis stage by 78%, 33%, 22%, and 33% at 24 weeks compared to the pretreatment, respectively [3]. Reduction of body weight and insulin resistance by SGLT2is may be largely associated with an improvement of liver function [4]. However, we have not fully understood the potential SGLT2i-induced mechanisms for an improvement of liver. Therefore, we discussed the possible underlying mechanisms for an improvement of liver function due to SGLT2is by reviewing literatures.

Reported mechanisms for an improvement of liver function due to SGLT2is are shown in Table 1 [5-13]. Four-week repeated administration of ipragliflozin improved not only hyperglycemia and hyperinsulinemia but also hyperlipidemia and hepatic steatosis in high-fat diet and streptozotocin-nicotinamide-induced type 2 diabetic mice [5]. In addition, ipragliflozin reduced plasma and liver levels of oxidative stress biomarkers and inflammatory markers, and improved liver injury [5]. Repeated administration of ipragliflozin to streptozotocin-induced type 1 diabetic rats for 4 weeks significantly improved hepatic steatosis and reduced liver levels of oxidative stress biomarkers and plasma levels of inflammatory markers, and improved liver injury [6]. The effect of ipragliflozin on non-alcoholic fatty liver disease (NAFLD) in rats fed a choline-deficient L-amino acid-defined (CDAA) diet was reported [7]. Five weeks after starting the CDAA diet, rats exhibited hepatic triglyceride (TG) accumulation, fibrosis, and mild inflammation. Repeated administration of ipragliflozin prevented hepatic TG accumulation, large lipid droplet formation and liver fibrosis. Ipragliflozin also improved hepatic steatosis in high-

fat diet-induced and leptin-deficient obese (ob/ob) mice irrespective of body weight reduction [8]. Ipragliflozin-induced hyperphagia occurred to increase energy intake, attenuating body weight reduction with increased epididymal fat mass. However, there is an inverse correlation between weights of liver and epididymal fat in ipragliflozin-treated obese mice, suggesting that ipragliflozin promoted normotopic fat accumulation in the epididymal fat and prevented ectopic fat accumulation in the liver. Such an effect of SGLT2is on hepatic fat accumulation was also reported in humans. Luseogliflozin was reported to reduce magnetic resonance imaging-hepatic fat content in type 2 diabetes patients with NAFLD [9, 10]. Very recently, empagliflozin effectively lowered liver fat content in well-controlled type 2 diabetic patients [11]. In this study, empagliflozin raised adiponectin levels [11], which has beneficial effects on glucose and lipid metabolism including activation of adenosine 5'-monophosphate (AMP)-activated protein kinase (AMPK) [14].

AMPK activation was also induced by canagliflozin, which was caused by inhibition of Complex I of the respiratory chain, leading to increases in cellular AMP or adenosine diphosphate (ADP) [12]. Canagliflozin inhibited lipid synthesis, an effect that was absent in AMPK knockout cells and that required phosphorylation of acetyl-CoA carboxylase (ACC) at the AMPK sites [12]. Another study also showed that SGLT2is ameliorated fat deposition and increased AMPK phosphorylation, resulting in phosphorylation of its major downstream target, ACC, in human hepatocytes, which led to the downregulation of downstream fatty acid (FA) synthesis-related molecules and the upregulation of downstream β oxidation-associated molecules [15]. Tofogliflozin reduced the body weight gain, mainly because of fat mass reduction associated with a diminished adipocyte size in C57BL/6 mice [13]. Serum-free FA and ketone bodies were increased and the respiratory quotient was decreased in the tofogliflozin-treated mice, suggesting the acceleration of lipolysis in adipose tissue and hepatic β -oxidation [13]. Hepatic TG contents were decreased. Further, tofogliflozin ameliorates insulin resistance and obesity by increasing glucose uptake in skeletal muscle and lipolysis in adipose tissue.

Empagliflozin shifted energy metabolism towards fat utilization, elevated AMPK and ACC phosphorylation in skeletal muscle in diet-induced obese mice [16]. SGLT2is induce a negative energy balance state by excreting glucose in the urine, which may induce alteration in glucose-FA cycle [17]. The fundamental concept of glucose-FA cycle is reciprocal substrate competition between glucose and FA in oxidative tissues such as skeletal muscles. By now, many new mechanisms

Manuscript submitted October 3, 2019, accepted October 18, 2019

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doi: <https://doi.org/10.14740/jocmr4019>

Table 1. Reported Mechanisms for an Improvement of Liver Function due to SGLT2is

SGLT2is	References	Subjects	Effects on liver and putative mechanisms to improve liver function
Ipragliflozin	[5]	Type 2 diabetic mice	Improvement of hepatic steatosis and liver injury; reduction of plasma and liver levels of oxidative stress biomarkers and inflammatory markers
Ipragliflozin	[6]	Type 1 diabetic rats	Improvement of hepatic steatosis and liver injury; reduction of liver levels of oxidative stress biomarkers and plasma levels of inflammatory markers
Ipragliflozin	[7]	NAFLD rats	Prevention of hepatic triglyceride accumulation, large lipid droplet formation and liver fibrosis
Ipragliflozin	[8]	Obese mice	Prevention of ectopic fat accumulation in the liver
Luseogliflozin	[9, 10]	Type 2 diabetic patients with NAFLD	Reduction of hepatic fat content
Empagliflozin	[11]	Well-controlled type 2 diabetic patients	Lowering of liver fat content
Canagliflozin	[12]	HEK-293 cells	AMPK activation by inhibition of Complex I of the respiratory chain; inhibition of lipid synthesis, by phosphorylation of ACC at the AMPK sites in human hepatocytes, which leads to downregulation of fatty acid synthesis-related molecules and upregulation of β oxidation-associated molecules
Tofogliflozin	[13]	C57BL/6 mice	Decrease of hepatic triglyceride content; acceleration of lipolysis in adipose tissue and hepatic β -oxidation

SGLT2is: sodium-glucose cotransporter-2 inhibitors; ACC: acetyl-CoA carboxylase; AMPK: adenosine 5'-monophosphate-activated protein kinase; NAFLD: nonalcoholic fatty liver disease; HEK: human embryonic kidney.

controlling the utilization of glucose and FA have been discovered [18]. Dysregulation of FA metabolism is a key event responsible for insulin resistance and type 2 diabetes [19]. We speculate that SGLT2i-mediated alteration of glucose-FA cycle may induce changes in glucose and lipid metabolism in skeletal muscle, adipose tissue and liver, which may be associated with amelioration of liver function.

In conclusion, the summary of possible underlying mechanisms for an improvement of liver function due to SGLT2is is shown in Figure 1. SGLT2is lead to reduction of renal glucose reabsorption and decrease of plasma glucose in an insulin-independent manner, inducing reduction of body weight and insulin resistance, which may be largely associated with an improvement of liver function. Increased renal excretion of glucose may alter glucose-FA cycle and may result in increase of FA use/oxidation in skeletal muscle and liver, and increase of lipolysis in adipose tissue. The improvement of insulin resistance and altered glucose-FA cycle may ameliorate glucose/lipid metabolic crosstalk between skeletal muscle, adipose tissue and liver, which may also contribute to an improvement of liver function. SGLT2is also induce activation of AMPK, which increases FA use/oxidation in skeletal muscle and liver, and decreases FA synthesis in liver. Decrease of hepatic fat accumulation by SGLT2is reduces oxidative stress and inflammation, which may induce amelioration of liver function.

Acknowledgments

We thank the staff (Yukie Kawamura, Keiko Nakamura, Harue Aoki and Ayano Sakakibara) of the Division of Research Support, National Center for Global Health and Medicine, Kohnodai Hospital.

Financial Disclosure

Authors have no financial disclosure to report.

Conflict of Interest

The authors declare that they have no conflict of interest concerning this article.

Informed Consent

Not applicable.

Author Contributions

HY designed the research, and MH and HK collected and analyzed data. HY wrote and approved the final paper.

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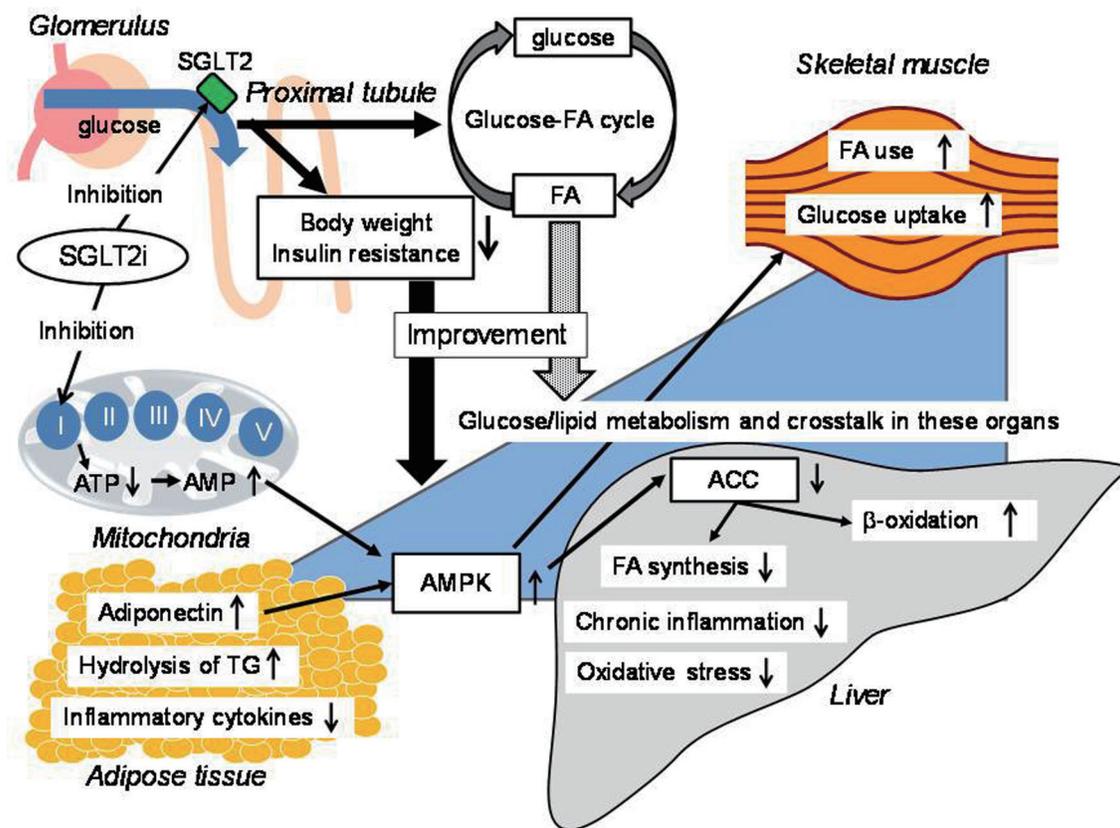


Figure 1. The possible underlying mechanisms for an improvement of liver function due to SGLT2is. ACC: acetyl-CoA carboxylase; AMPK: adenosine 5'-monophosphate-activated protein kinase; FA: fatty acid; SGLT2is: sodium-glucose cotransporter-2 inhibitors; TG: triglyceride; AMP: adenosine 5'-monophosphate; ATP: adenosine triphosphate.

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