Novel I1-Imidazoline Agonist S43126 Augment Insulin Secretion in Min6 Cells

Jerusalem Tesfai1, Louis Crane2, Genevieve Baziard-Mouysset3 and Lincoln P. Edwards*3

1Department of Biochemistry, Loma Linda University School of Medicine, Loma Linda, CA, USA
2Laboratoire de Chimie Pharmaceutique, Universite Paul Sabatier, Faculte de Pharmacie, USA
3Center for Dental Research, School of Dentistry and School of Medicine, Loma Linda University, Loma Linda, CA, USA

Abstract

The I1-imidazoline receptor is a novel drug target for hypertension and insulin resistance which are major disorders associated with Type II diabetes. In the present study, we examined the effects of a novel imidazoline agonist S43126 on calcium fluxes and insulin secretion from Min6 β-cells. We also examined the effects of S43126 on the induction of IRAS, and phosphorylation of components in the I1-imidazoline signaling pathways, namely ERK and PKB. Min6 β-cells were treated with varying doses of S43126 [10-6M to 10-3M] for various time (5-60mins), S43126 at higher dose [10-5M] stimulated insulin secretion under elevated glucose concentration compared to basal. In addition, insulin secretion and Ca2+ influx mediated by S43126 [10-5M] were decreased following co-treatment with efaxoxan (I1-antagonist) and nifedipine (L-type voltage-gated Ca2+-channel blocker) at various times (5-60mins). Furthermore, S43126 at [10-5M] increased Ca2+ oscillation, [Ca2+]i and 45Ca2+ uptake in a time and dose-dependent manner. Moreover, Western blot analysis of treated samples showed that S43126 caused an increased protein expression of IRAS as well as phosphorylation of both ERK1/2 and PKB in a concentration-dependent manner. We conclude that S43126 exerts its insulinotropic effect in a glucose dependent manner by a mechanism involving L-type calcium channels and imidazoline I1-receptors.

Introduction

Insulin resistance and hypertension are commonly associated with metabolic syndrome, which affects over 75 million Americans, and type 2 diabetes which affects over 18 million Americans [1]. Pharmacologic treatment of many type 2 diabetic patients requires separate agents for treating hyperglycemia, and hypertension. This results in patients having to take multiple medications, which negatively impact patient compliance and increases the risk for drug interaction. In response to this growing health care problem, compounds that have the ability to counter both hyperglycemia and hypertension would positively impact compliance and be an asset to patients.

Pharmacologic criteria have defined three main types of imidazoline receptors: the I1 subtype is labeled by [3H] clonidine and the I2 subtype is labeled by [3H] idazoxan [2,3]. A third pharmacologically distinct entity, the I3 subtype, is found in the pancreas and is involved in regulation of insulin secretion [4]. Functionally, I1-imidazoline sites seem to play a role in depression as the density of I1-sites were altered in suicide/depressive patients and the I2-selective compound 2-(2-benzofuranyl)-imidazoline (2-BFI) demonstrated antidepressant-like effects in mice according to the tail suspension test and the forced swim test [5]. The I3-site is also an emerging drug target for pain treatment [6] and I1-agonists have been shown to enhance the antinoceptive effects of opioids [7]. There is an emerging role for I1-agonists in the regulation of glucose homeostasis. Cerebral injections of agmatine reduced plasma glucose levels in streptozotocin-induced diabetic (STZ-diabetic) rats by a mechanism not involving insulin secretion but activation of I1-imidazoline receptors [8]. It was subsequently shown that peripheral administration of agmatine caused activation of I1-receptors in the adrenal medulla to enhance secretion of β-endorphins, leading to activation of μ-opioid receptors, and lower glucose levels [9]. Additionally it was shown that in rats where insulin resistance was induced by a high fructose diet, agmatine (1mg/kg) ameliorated the insulin resistance by a mechanism involving I1-imidazoline receptors [10].

Imidazoline compounds, which are agonists at the I1-imidazoline receptor (I1R) present in the rostral ventrolateral medulla (RVLM) region of brain [11,12] act centrally to lower blood pressure. Clinical and basic findings also indicate a role for I1-imidazoline agonists in the treatment of insulin resistance and diabetics with hypertension [13,14].

Several studies have shown that compounds containing the imidazoline moiety are potent stimulators of insulin secretion from pancreatic β-cells [15-19]. The mechanisms by which imidazoline compounds promote insulin secretion have not been fully elucidated. Classical imidazoline compounds mimic the actions of sulfonylurea drugs and interact directly with the pore-forming component (Kir6.2) of the ATP-sensitive potassium (KATP) channel to promote channel closure, membrane depolarization, Ca2+ influx and insulin secretion [15,17,20,21]. These agents also have a direct effect on exocytosis. Other imidazoline compounds have been shown to have no effect on the KATP channel, but exert their insulinotropic effects only if glucose concentration is elevated [18]. Some agents show a dependence on protein kinase A and C to exert their insulinotropic effects [18].

We have previously shown that S43126 (pK1, I1=7.46, pK, I2=8.28, pK, a≤5 and pK,a≤5) a novel imidazoline compound with close binding affinities for both I1 and I2, imidazoline binding sites [22], lowers blood pressure when injected into the RVLM of spontaneously hypertensive rats. This compound does not contract rat tail arterial strips suggesting
that it is inactive at alpha adrenergic receptors [23]. In this study we
describe the effects of S43126 on calcium fluxes, insulin secretion and
glucose uptake. Imidazoline compounds may prove useful in treating
diabetics with hypertension

Materials and Methods

Antibodies and reagents

Primary antibodies used were IRAS, β-actin, p44/42 MAP kinase,
phospho-p44/42 MAP kinase (Thr202/Tyr204), Akt, phospho-
Akt (Ser473) antibody diluted 1:1000, which were detected using a
secondary antibody (HRP linked anti-rabbit IgG), diluted 1:2000
and enhanced chemiluminescence (ECL, Amershams Pharmacira Biotech).
Treated cells were lysed and aliquots were subjected to western blotting
using appropriate antibodies.

Cell culture and drug treatment

Min6 β-cells were cultured in DMEM (Cellgro) supplemented with
15% FBS, 5mL penicillin/streptomycin solution (Sigma), 1 µL
β-mercaptoethanol (Sigma) and maintained in the presence of 5% 
CO2 at 37°C. Min6 β-cells were treated with varying doses of S43126
[10⁻⁵M-10⁻²M] for different times, in the presence or absence of 1- imidazoline receptor blocker efaroxan [100µM] or L-type calcium
channel blocker nifedipine [10µM].

Single-cell microfluorimetry

Min6 β-cells were seeded on 25 mm glass coverslips in 35 mm plastic dishes. Twenty-four hours before imaging, culture medium
was replaced with serum free medium. On the day of the experiment, 
culture medium was removed; cells were washed twice with Krebs-
Ringer bicarbonate (KRB) buffer, pH 7.5, and containing 2.8 mM

glucose. Washed cells were incubated with KRB/calcium 2 hours for 37
°C. Min6 β-cells were treated with preincubations of S43126
[10⁻⁵M] for various times, in the presence or absence of S43126. Under conditions of high glucose, the maximal release of
insulin was 3.1 fold, seen at 5 mins of treatment with 10⁻⁵M S43126.
Under conditions of high glucose, the maximal release of insulin was 2.3 fold, seen at 5 mins of treatment with 10⁻⁵M S43126.
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Insulin secretion

Monolayers of Min6 β-cells were seeded 3 days before each series of
studies in 24-well plates at a density of 500,000 cells per well. 12 hours
before each experiment, the culture medium was replaced with serum
free medium. On the day of the experiment, the cells were washed twice
with KRB buffer, pH 7.5, containing 0.1% BSA (KRB-BSA). Cells were
then preincubated for 2 hrs in KRB-BSA containing 2.8 mM glucose at
37°C, 5% CO2, followed by incubated for 2 hours in KRB-BSA containing
various concentration of effectors (S43126, efaroxan and nifedipine) and
glucose (2.8mM or 16.7mM) [13]. After incubation, the medium
was collected, centrifuged at 600 x g for 10 mins and stored at -20°C.
Insulin release was measured using Meredia ultrasensitive mouse
insulin enzyme-linked immunoassay kit (ELISA) kit (Merodia AB,
Uppsala, Sweden). Protein concentrations were determined using the
BioRad DC Protein assay reagents (BioRad, Hercules, CA).

Statistical analysis

Data was analyzed using two-way analysis of variance (ANOVA) or
Tukey’s test for pair-wise multiple comparisons to identify
dependent variables (P<0.05) between individual samples. Percent blockade
was calculated using the formula % blockade = (S - [S+N])/(S - baseline) *
100 (Figure 3 and 4).

Results

Effects of S43126 on insulin secretion

We examined the ability of S43126 [10⁻⁵M-10⁻²M] to induce insulin
secretion directly from Min6 β-cells at various times (5-60mins)
under conditions of basal glucose (2.8mM) and high glucose (16.7mM). 
S43126, a novel 1-imidazoline agonist (Figure 1), induced a dose-
dependent release of insulin at 5 mins, 10 mins and 30 mins under
conditions of basal glucose (Figure 2A), and under high glucose (Figure 2B).
At 5 mins and 10 mins, the amount of insulin release caused by a
particular dose of S43126 was greater under conditions of high glucose
than at basal glucose. Under conditions of basal glucose, the maximal
release of insulin was 2.3 fold, seen at 5 mins of treatment with 10⁻⁵M
S43126. Under conditions of high glucose, the maximal release of insulin was 3.1 fold, seen at 5 mins of treatment with 10⁻⁵M S43126.
Relative insulin secretion decreased with time following stimulation
under basal and high glucose.

In order to evaluate the role of 1-imidazoline receptor and L-type calcium
channel in the insulinotrophic effect of S43126, we treated Min 6

cells with S43126 [10⁻⁵M] in the presence or absence of either efaroxan
[100µM] (1-antagonist) or nifedipine [10µM] (L-type calcium channel
blocker) for various times (5-60mins). We used S43126 [10⁻⁵M] as this
dose produced the maximum release of insulin in our previous study.
Under conditions of basal glucose, efaroxan caused 92%, 50%, 166%,
and 85% inhibition of insulin release by S43126 at 5 mins, 10 mins, 30
mins, and 60 mins respectively (Figure 3A). Efaroxan by itself caused
release of insulin under both basal and high glucose conditions.

Figure 1: Chemical Structure of the Novel Imidazoline Compound, S43126.
conditions of high glucose, efaroxan caused a greater than 89%, 100%, 93%, 100% inhibition of insulin release by S43126 at 5 mins, 10 mins, 30 mins and 60 mins respectively (Figure 3B).

Co-treatment of Min 6 cells with nifedipine [10μM], caused an approximately 73%, 63%, 91% and >80% reduction in insulin release at 5mins, 10 mins, 30 mins and 60 mins respectively under basal glucose conditions (Figure 4A). Inhibition of insulin release by nifedipine was more dramatic under high glucose conditions. Nifedipine caused a greater than 90% reduction in insulin release at all time points (Figure 4B).

**Effects of S43126 on [Ca^{2+}]**

When Min6 β-cells were incubated with S43126 [10^{-5} M - 10^{-3} M] in the presence of 2.8mM glucose, S43126 caused a dose-dependent increase in [Ca^{2+}], which was first observed at [10^{-4} M] of S43126 (Figure 5A). The amplitude of the calcium oscillations evoked by S43126 at 2.8mM glucose were less than those produced by 16.7mM glucose, but greater than control, at higher doses. The increase in [Ca^{2+}], caused by S43126 [10^{-5} M] and 2.8mM glucose were similar at 1 min, however S43126 [10^{-3} M] caused a gradual increase in [Ca^{2+}] up to 5min followed by a slight decline. Under conditions of basal glucose, [Ca^{2+}] gradually declined with time. The temporal response of [Ca^{2+}] to high glucose, mimics that of S43126 [10^{-3} M] but with higher levels of [Ca^{2+}], (Figure 5B).

**Effects of S43126 on ^{45}Ca^{2+} uptake**

Min 6 cells were also incubated with ^{45}Ca^{2+} alone or in combination with S43126 [10^{-3} M] at various times (0-60 mins). There was a time-dependent increase in ^{45}Ca^{2+} influx up to 5 mins, followed by a decline at 10 mins and then a plateau between 30-60 mins (Figure 6A). The maximum influx of greater than 3 fold was seen at 5 mins. Since S43126 [10^{-3} M] provoked marked ^{45}Ca^{2+} influx at 5 mins, we co-treated cells with S43126 [10^{-3} M] in the presence or absence of either efaroxan (10 μM) or nifedipine (10 μM) with the aim of determining whether I_{1-imidazoline} receptor or L-type calcium channels mediated the observed ^{45}Ca^{2+} influx into Min 6 cells. S43126 increased ^{45}Ca^{2+} influx by 4 fold and this increase was blocked by efaroxan (Figure 6B).
In addition, nifedipine, a blocker of L-type calcium channels, reduced \( \text{Ca}^{2+} \) influx by S43126 to near basal levels (Figure 6B).

### Effects of S43126 on ERK1/2, PKB phosphorylation and IRAS protein expression

S43126 [10^{-5}M-10^{-8}M] induce IRAS protein expression in a dose-dependent manner (Figure 7A). S43126 [10^{-7}M-10^{-5}M] also cause a 3-fold increase in ERK1/2 phosphorylation (Figure 7B) and a 2-fold increase in PKB phosphorylation (Figure 7C). ERK1/2 and PKB are components of both the insulin and imidazoline receptor signaling pathways.

### Discussion

Compounds that have the ability to treat both hypertension and insulin resistance would greatly improve compliance among patients. The novel imidazoline compound S43126 has been shown previously to lower blood pressure in rats following injection into the RVLM, but did not contract rat tail artery [23]. We therefore wanted to determine whether S43126 also had the ability to affect glucose homeostasis. Treatment of Min6 \( \beta \)-cells with S43126 caused a dose-dependent increase in insulin secretion at 5 mins, 10 mins and 30 mins under conditions of basal glucose (Figure 2A), and under high glucose (Figure 2B). This increase in insulin secretion was modest, but glucose-dependent, with S43126 causing a greater insulin release at higher concentrations of glucose at 5 mins and 10 mins. This is in contrast to sulfonylurea drugs which demonstrate a strong insulinotropic effect at basal glucose concentrations. Agents that stimulate robust insulin secretion at basal levels of glucose are more likely to cause hypoglycemia in patients [27]. A more desirable therapeutic outcome would be achieved by agents such as S43126 that augment glucose-induced insulin secretion.

The effect of imidazoline compounds on glucose homeostasis is mediated by all three subtypes of imidazoline receptors. L\(_{\text{-imidazoline}} \) and L\(_{\text{-imidazoline}} \) agonists mediate insulin release, while L\(_{\text{-imidazoline}} \) agonists mediate insulin sensitization. It was shown previously that cerebral injections of agmatine caused a decrease in plasma glucose in STZ-diabetic rats, but plasma levels of glucose and insulin were not affected in normal rats [8]. This suggested that agmatine was acting through a non-insulin dependent mechanism, and did not cause insulin release in normal rats. The effects of agmatine on glucose levels would be achieved by agents such as S43126 that augment glucose-induced insulin secretion.
the peripheral glucose lowering effects of agmatine involved secretion of β-endorphins from the adrenal medulla, secondary to activation of adrenal I₂-imidazoline receptors. β-endorphins are known to decrease the gene expression of phosphoenolpyruvate carboxykinase (PEPCK), a key enzyme in gluconeogenesis [9]. Increased GLUT4 gene expression was also involved in the glucose lowering effects of agmatine [9].

The novel compound S4321 has affinity at I₂-imidazoline receptors, since as stated above, agmatine which also has effects at I₂-imidazoline receptors does not cause insulin release in normal rats. In addition, I₂-ligands such as cirazoline and idazoxan were shown to cause insulin release from RIN-5AH insulinoma cell line, but not by their actions at I₂-imidazoline receptors, since irreversible blockade of the I₂-receptor by clorgyline did not attenuate the effects of these compounds on insulin secretion. The proposed mechanism for insulin release by these ligands was an action on Kᵢᵥ channels [28].

Imidazoline compounds are not uniform in the mechanism by which they stimulate insulin release from pancreatic beta cells. Some imidazolines such as efaroxan [29,30], phentolamine [31] and RX871024 [32-33] stimulate insulin secretion both in vivo and in vitro by binding to Kᵢᵥ channels [29-34]. The pore forming subunit of the Kᵢᵥ channel, Kir6.2 contains an imidazoline binding site [35] to...
which certain imidazolines bind, leading to membrane depolarization, activation of voltage-dependent calcium channels, and subsequent calcium influx, and insulin secretion. Some imidazolines such as BL11282 stimulate insulin secretion only at elevated levels of glucose and does not block the K-ATP channel [18]. This property suggests that the risk of hypoglycemia would be very low in patients treated with BL11282. However, we are unaware of any published data suggesting that BL11282 lowers blood pressure. Thus BL11282 may not possess the utility that S43126 has in impacting both hypertension and insulin resistance. 

S-21663 is an imidazoline compound that is a non glucose-dependent insulin secretagogue, which does not readily induce hypoglycemia [15]. The authors explained the discrepancy between the ability of S-21663 to stimulate insulin secretion at all levels of glucose and the lack of hypoglycemia seen in vivo by the existence of some compensatory mode of action by this compound in vivo, but not seen in vitro. S-21663 acts in a manner that is dependent on calcium entry via L-type calcium channels that are activated by closure of non K-ATP potassium channels [15]. Our novel compound S43126 also caused an increase in intracellular calcium via influx through nifedipine sensitive calcium channels. Unlike other imidazolines, we showed that the insulinotopic effect of S43126 could be blocked by efaroxan, an 1-imidazoline antagonist. In addition to its antagonistic effect at 1-imidazoline sites, efaroxan can also interact with K-ATP channels or the 1-imidazoline receptor to cause insulin release. We observed that efaroxan did cause release of insulin presumably through its action at K-ATP channels or the 1-imidazoline receptor. Combination of S43126 and efaroxan resulted in inhibition of insulin release; this suggested that at 100 µM, efaroxan acted as an effective blocker of the 1-receptor. The degree of antagonism caused by efaroxan was complicated by its ability to release insulin and a purer antagonist would prove more useful. The functional effects of S43126 at the various subtypes of imidazoline receptors need to be further studied, using inhibitors without intrinsic effects at these receptors.

S43126 also caused an increased induction of IRAS protein, and an increased phosphorylation of ERK and PKB which are components of the 1-imidazoline signaling pathways. In one study, PKB function in beta cells was disrupted by expression of a kinase-dead dominant negative form of PKBα (rip-kipkpb) and defective insulin secretion was observed, but no reduction in islet size [36]. This suggests that at least PKBα may play a role in insulin secretion. There is some controversy surrounding the exact role of different isoforms of PKB in the pancreas. Recent work by Buzzi et al. [37] showed that only PKBα but not PKBβ or PKBγ is activated downstream of IRS2 in beta cells. Overexpression of PKBα by adenovirus caused an increased proliferation of beta cells, while overexpression of PKBγ and PKBβ were ineffective. In another study, it was shown that PKBα-deficient mice can show enhanced glucose tolerance in addition to improved beta cell function and higher insulin sensitivity in adipocytes. Further studies will be needed to determine the importance of increased phosphorylation of PKB by S43126 on insulin sensitivity, and any possible involvement of 1-imidazoline receptors. These studies will need to consider the specific isoforms of PKB, which, as the recent studies showed, may even have opposing effects [37].

In conclusion, S43126 is a novel compound that activated 1-imidazoline receptors but not α-adrenoceptors [23,38]. We have shown that S43126 induced insulin secretion in a dose and time dependent manner. Because S43126 increased insulin release at higher glucose levels compared to basal condition, the risk of hypoglycemia associated with the use of S43126 is diminished [9]. Thus, the present study showed that S43126 activated at least two distinct mechanisms to promote insulin release. One of these may involve binding to imidazoline 1-receptors, while a second arises from calcium influx due to L-type Ca2+ channels. More importantly, S43126 activated components of the 1-imidazoline signaling pathways, namely IRAS, ERK and PKB in Min6 β-cells have the potential to act as an insulin sensitizer. Imidazoline agonists should be developed as an innovative pharmacological approach for the management of Type II diabetes.

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References


