Research Article

Repurposing Lesogaberan to Promote Human Islet Cell Survival and β-Cell Replication

Jide Tian, Hoa Dang, Angela Hu, Willem Xu, and Daniel L. Kaufman

Department of Molecular and Medical Pharmacology, University of California, Los Angeles, CA, USA

Correspondence should be addressed to Daniel L. Kaufman; dkaufman@mednet.ucla.edu

Received 12 May 2017; Accepted 26 July 2017; Published 5 September 2017

Academic Editor: Peter Thule

Copyright © 2017 Jide Tian et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The activation of β-cell’s A- and B-type gamma-aminobutyric acid receptors (GABAA-Rs and GABAB-Rs) can promote their survival and replication, and the activation of α-cell GABAA-Rs promotes their conversion into β-cells. However, GABA and the most clinically applicable GABA-R ligands may be suboptimal for the long-term treatment of diabetes due to their pharmacological properties or potential side-effects on the central nervous system (CNS). Lesogaberan (AZD3355) is a peripherally restricted high-affinity GABAB-R-specific agonist, originally developed for the treatment of gastroesophageal reflux disease (GERD) that appears to be safe for human use. This study tested the hypothesis that lesogaberan could be repurposed to promote human islet cell survival and β-cell replication. Treatment with lesogaberan significantly enhanced replication of human islet cells in vitro, which was abrogated by a GABAB-R antagonist. Immunohistochemical analysis of human islets that were grafted into immune-deficient mice revealed that oral treatment with lesogaberan promoted human β-cell replication and islet cell survival in vivo as effectively as GABA (which activates both GABAA-Rs and GABAB-Rs), perhaps because of its more favorable pharmacokinetics. Lesogaberan may be a promising drug candidate for clinical studies of diabetes intervention and islet transplantation.

1. Introduction

A major goal in diabetes research is to develop agents that can safely promote human β-cell survival and replication. Most mitogens and growth factors that have been shown to promote rodent β-cell replication fail to promote human β-cell replication (reviewed in [1, 2]). β-Cells have been long known to express the GABA synthetic enzyme glutamic acid decarboxylase (GAD), as well as GABAA-Rs and GABAβ-Rs [3–7]. Although GABAα-Rs and GABAβ-Rs share GABA as an agonist, these receptors are encoded by distinct gene families and their activation induces different pathways; GABAα-Rs are fast-acting chloride channels and GABAβ-Rs are slow-acting G-protein-coupled receptors [8, 9]. Recently, GABA administration has been shown to protect rodent and human β-cells from apoptosis and to promote their replication both in vitro and in vivo [10–14]. This response is mediated by both GABAα-R and GABAβ-Rs [10–12, 14, 15]. GABA-mediated enhancement of β-cell replication did not attenuate after five weeks of GABA treatment and led to an eventual increase in β-cell mass in a nonautoimmune context [14]. Notably, GABA treatment enhanced β-cell replication and survival in newly diabetic NOD mice [11, 16, 17], indicating that GABA-R activation can be beneficial in an autoimmune context even when little β-cell mass remains.

β-Cells express GABAα-Rs and GABAβ-Rs [3, 4, 7, 18, 19]. α-Cells express GABAα-Rs but may not express functional GABAβ-Rs, while PCR detects GABAβ-R transcripts in isolated α-cells (but not the α-cell line α-TC9), a GABAβ-R agonist failed to modulate any of the tested α-cell functions [3, 18–21]. We are unaware of any evidence of functional GABAβ-Rs on δ or PP islet cells. Very recently, long-term treatment with antimalarial drugs that target gephyrin (a protein that participates in GABAα-R transport to the membrane), or treatment with GABA, was shown to promote islet α-cell transdifferentiation into β-cells [22, 23].
This conversion appears to be mediated by GABA\textsubscript{A}-Rs [22, 23] and not the GABA\textsubscript{B}-Rs that are the focus of this study. GABA appears safe for human consumption [24] and its inability to pass through the blood-brain barrier (BBB) avoids potential CNS effects. GABA, however, has a relatively low affinity for its receptors, a fast off-rate (presumably so that neurons can quickly respond to the next stimulus), and a short half-life (about 20 minutes in blood [25]) and therefore may be pharmacologically suboptimal. In the clinic, there are many BBB-permeable drugs that can modulate neuronal GABA-Rs and ameliorate CNS disorders such as seizures, anxiety, and insomnia. Their CNS effects, however, raise concerns about their long-term use for the treatment of diabetes. It would be ideal if peripherally restricted GABA-R agonists that were safe for human use could be repurposed for treating diabetes.

Lesogaberan (AZD3355) is a peripherally restricted GABA\textsubscript{B}-R-specific agonist that was developed for the treatment of GERD [26–28]. It has an EC\textsubscript{50} of 9 nM (compared to GABA’s EC\textsubscript{50} of 160 nM) and a K\textsubscript{d} of 5 nM (versus 110 nM for GABA) for GABA\textsubscript{B}-Rs [26] and a half-life of about 11 hours in peripheral blood [29, 30]. While treatment of GERD patients with lesogaberan (oral 60–240 mg twice daily) for up to 28 days in several phase Ib clinical trials did not result in sufficient beneficial effects, there were no treatment-related serious adverse events, suggesting that lesogaberan may be safe for human use [27, 29, 31]. Here, we tested the potential of repurposing lesogaberan to promote human islet cell survival and β-cell replication. Our findings suggest that targeting GABA\textsubscript{B}-Rs can promote human β-cell replication and islet cell survival to a similar extent as GABA.

2. Materials and Methods

2.1. Chemicals. Lesogaberan was supplied by AstraZeneca (London, UK). The development and structure of lesogaberan have been previously described [28]. Saclofen, streptozotocin (STZ), and 5-bromo-2-deoxyuridine (BrdU) were purchased from Sigma Aldrich.

2.2. Islet Cell Proliferation Assay. Fresh human islets were obtained from the Integrated Islet Distribution Program (IIDP). The islets (50–75 IEQ/well) were treated in triplicate with, or without, the indicated dosages of lesogaberan in CMRL medium (0.1% glucose, Gibco) containing 10% human AB-type sera (MP Biomedicals, Santa Ana, USA) and 1.5 μCi/ml of \(^3\)H-thymidine in the presence or absence of the competitive GABA\textsubscript{B}-R antagonist saclofen (10\textsuperscript{-4} M) for 4 days. Islets cultured in medium alone served as controls. The \(^3\)H-thymidine uptake in individual wells was measured by β-counter. Data were analyzed by the proliferation index formula: CPM of experimental wells / CPM of controls.

2.3. Analysis of Human β-Cell Replication In Vivo. All animal experiments were approved by UCLA’s Animal Research Committee. NOD/scid mice were injected intraperitoneally with STZ to induce diabetes and implanted with about 2000 human islets under their kidney capsule. The mice were randomized and treated for 12 days with plain water containing 0.8 mg/ml of BrdU as the control or water containing the same dose of BrdU and lesogaberan (0.08 mg/ml) or positive control GABA (6 mg/ml). At the end of treatment, the percentages of BrdU\textsuperscript{+}insulin\textsuperscript{+} and Ki67\textsuperscript{+}insulin\textsuperscript{+} β-cells in at least 2000 islet cells of 10 fields (magnification ×400) of each islet graft were determined by immunofluorescence in a blinded manner, as our previous report [12].

2.4. Analysis of Human β-Cell Apoptosis In Vivo. STZ-rendered diabetic NOD/scid mice were implanted with about 2000–3000 human islets under their kidney capsule. The mice were randomized and given plain water or water containing lesogaberan (0.08 mg/ml) or positive control GABA (6 mg/ml). Forty-eight hours later, the percentages of insulin\textsuperscript{+} β-cells or TUNEL\textsuperscript{+} apoptotic islet cells in total islet cells within the grafts of individual recipients were determined by immunofluorescence in a blinded manner, as in our previous report [12].

2.5. Statistical Analysis. Data are expressed as the mean ± SEM of individual groups (n = 4–9 mice per group) from two separate experiments. The difference among groups was analyzed by ANOVA and post hoc Fisher’s least significant difference and the difference between groups was determined Student t-test. A p value of <0.05 was considered statistically significant.

3. Results

3.1. Lesogaberan Enhances Human Islet Cell Proliferation In Vitro. Human islets were treated with lesogaberan over a dose range in the presence, or absence, of the GABA\textsubscript{B}-R competitive antagonist saclofen. The effect of drug treatment on islet cell proliferation was determined by \(^3\)H-thymidine incorporation. We observed that lesogaberan at 3 nM had a small but nonsignificant promitotic effect, while treatment at higher dosages (10 and 30 nM) led to a 2-3-fold increase in proliferation relative to that of islets cultured in medium alone (Figure 1). Lesogaberan effects were not dose-dependent at the concentrations tested, and this may reflect its bimodal effect that was noted in some early preclinical GERD studies [26], but was not observed in subsequent clinical studies [27, 29, 31–33]. The promitotic effect of lesogaberan was blocked by saclofen (Figure 1). Hence, activation of GABA\textsubscript{B}-Rs enhanced human islet cell proliferation in vitro.

Since β-cells may be the only islet cell type that expresses functional GABA\textsubscript{B}-Rs and α-cell transdifferentiation would require long-term GABA\textsubscript{A}-R activation and would not involve \(^3\)H-thymidine incorporation into new DNA, the vast majority of the proliferating islet cells are likely to be β-cells. That contention, however, requires verification, which we pursued using quantitative immunohistochemical analysis of β-cells in human xenografts below.

3.2. Oral Lesogaberan Promotes Human β-Cell Replication In Vivo. Next, we quantitatively assessed lesogaberan’s effects on human β-cell replication in vivo. We implanted ~2000 human islets under the kidney capsule of STZ-rendered diabetic NOD/scid mice. Islet recipients were provided with
Lesogaberan + insulin+ and Ki67+ insulin+ islet recipients, including controls given plain water, quickly became normoglycemic after receiving dosing studies. All islet recipients, including controls given saclofen (10−4 M) for 4 days. Data shown are the average rate of proliferation ± SEM relative to that of cultures with medium alone (designated as 1) using islets from two donors, each of which were studied in separate experiments. Treatment with saclofen alone did not affect the proliferation of human islet in our experimental system (data not shown). *p < 0.01 versus lesogaberan.

Lesogaberan enhances human islet cell proliferation in vitro. Human islets were treated in triplicate with, or without, the indicated dosages of lesogaberan in the presence (black bars) or absence (open bars) of saclofen (10−5 M) for 4 days. Data shown are the average rate of proliferation ± SEM relative to that of cultures with medium alone (designated as 1) using islets from two donors, each of which were studied in separate experiments. Treatment with saclofen alone did not affect the proliferation of human islet in our experimental system (data not shown).

4. Discussion

The modulation of GABA-Rs on β-cells is emerging as a new strategy to help promote human β-cell survival and replication in the context of T1D. Although GABA is safe for human consumption, its pharmacokinetics may be suboptimal. There are a number of available drugs that have been in wide clinical use to modulate GABA-Rs on CNS neurons; however, their CNS effects raise concerns for long-term diabetes treatment. We chose to test lesogaberan’s potential for diabetes treatment based on (1) its high affinity for GABA_B-Rs, (2) its peripheral restriction circumvents CNS effects, and (3) its apparent safety in early clinical studies. Our initial studies showed that lesogaberan at low dosages (30 and 10 nM) increased human islet cell proliferation in vitro by about 2-3-fold (resp.). This promitotic effect was abrogated by a GABA_A-R antagonist, confirming that the effect was mediated through GABA_B-Rs. The proliferating islet cells are likely to be primarily β-cells because β-cells may be the only islet cell type that express functional GABA_B-Rs and α-cell transdifferentiation requires long-term GABA_A-R activation [22].

After implanting human islets into scid mice, lesogaberan significantly increased β-cell replication in the islet grafts. The level of lesogaberan-induced β-cell replication in vivo was similar to that induced by GABA at the dosages used in our model and similar to the maximum level of β-cell replication that takes place shortly after birth in humans [37]. The activation of β-cell GABA_B-Rs causes the opening of potassium channels, release of Ca2+ from intracellular storage, PKA activation, and Ca2+-dependent activation of PI3K-Akt and CREB (reviewed in [14]). It is notable that lesogaberan promoted β-cell replication as effectively as GABA (which activates both GABA_B-Rs and GABA_A-Rs) which may be due to its superior pharmacokinetics. Our short-term treatments with lesogaberan and GABA should not have induced α-cell transdifferentiation (which became detectable after 2 months of GABA_A-R activation [22, 23]), and the small increase they induced in β-cell replication should not alter islet size. Finally, we observed that...
Lesogaberan treatment significantly preserved human islet cells from apoptosis in human islet grafts. It is thought that the amount of residual β-cell mass following T1D onset is a major factor determining the success of interventional therapy such that even a short-term treatment with lesogaberan may help preserve residual β-cell mass and thereby improve the outcome of interventional therapies. Indeed, GABA treatment enhanced β-cell replication and survival in newly diabetic NOD mice [11, 16], demonstrating that GABA-R activation can be beneficial in an autoimmune context even when there is little residual β-cell mass. It is worth noting that using FDA guidelines for scaling mouse doses to the equivalent human dosage (http://www.fda.gov/downloads/Drugs/.../Guidances/UCM078932.pdf), the lesogaberan dose we used was about 2- to 7-fold lower than the doses used in phase IIb GERD clinical trials [27, 32, 33]. This suggests that it may be possible to use lower dosage lesogaberan for diabetes treatment.

Conceivably, long-term lesogaberan treatment may lead to increased β-cell mass in T1D patients if autoimmune responses can be sufficiently controlled. In regard to controlling β-cell autoimmunity, recent studies indicate that activation of GABA_B-Rs on immune cells has anti-inflammatory effects and can ameliorate collagen-induced arthritis and contact dermatitis in mouse models [38, 39]. Therefore, lesogaberan may also have anti-inflammatory effects that help control the pathogenic autoreactive T-cell responses that mediate β-cell destruction in T1D. It will be of interest to further investigate how activation of GABA_B-Rs modulates the functions of different types of immunocompetent cells, and this may be a fertile area for new anti-inflammatory drug development. Additionally, lesogaberan may be combined with other immune modulators to potentially increase therapeutic effects, as was shown by the synergistic effect of combining GABA and antigen-specific immunotherapy to reverse hyperglycemia in newly diabetic NOD mice [16].

5. Conclusions
We found that the GABA_B-R agonist lesogaberan promoted human islet cell proliferation in vitro, as well as β-cell

Figure 2: Oral lesogaberan promotes human islet β-cell replication in mice. Mildly hyperglycemic NOD/scid mice were transplanted with human islets under their kidney capsule. The mice were randomized and provided with water containing with BrdU, with or without GABA (6 mg/ml) or lesogaberan (0.08 mg/ml) for 12 days. The percentages of replicated β-cells were determined by immunofluorescent assays using anti-insulin and anti-BrdU or anti-Ki67, followed by counterstaining with DAPI. (a) Representative image of islet cells (magnification ×400) costained with anti-insulin (green) and anti-BrdU (red) (arrows). (b) Representative image of islet cells costained with anti-insulin (green) and anti-Ki67 (red) (arrows). (c) Graphical representation of the percentages of BrdU’insulin+ β-cells and (d) Ki67’insulin+ islet cells in total insulin+ β-cells. Data are mean ± SEM from two independent experiments, each using islets from a human donor that were implanted into 4–9 NOD/scid mice. The percentages of BrdU’insulin+ and Ki67’insulin+ β-cells in at least 2000 islet cells of 10 fields of each islet graft were determined as described in Materials and Methods. *p < 0.05, **p < 0.01 versus the control.
replication and islet cell survival in vivo, as effectively as GABA. Accordingly, GABAB-R agonists may provide a new drug class to help maintain residual β-cell mass and function after diabetes onset. Our findings also suggest that including lesogaberan in the drug regimen following clinical human islet transplantation for even a brief period may reduce β-cell loss due to stressors and may thereby reduce the number of islets required to achieve insulin independence. Lesogaberan’s apparent safety and pharmacokinetic profile make it an excellent candidate for testing in clinical trials.

Conflicts of Interest

The authors declare that there is no duality of interest associated with this manuscript.

Acknowledgments

The authors thank the IIDP for providing isolated human islets. This work was supported by a grant from the JDRF (17-2013-403) and the National Institutes of Health (DK092480) to Daniel L. Kaufman.

References

[1] S. Bonner-Weir, W. C. Li, L. Ouziel-Yahalom, L. Guo, G. C. Weir, and A. Sharma, “β-Cell growth and regeneration: replication is only part of the story,” Diabetes, vol. 59, no. 10, pp. 2340–2348, 2010.
[2] R. N. Kulkarni, E. B. Mizrachi, A. G. Ocana, and A. F. Stewart, “Human β-cell proliferation and intracellular signaling: driving in the dark without a road map,” Diabetes, vol. 61, no. 9, pp. 2205–2213, 2012.
[3] P. Rorsman, P. O. Berggren, K. Bokvist et al., “Glucose-inhibition of glucagon secretion involves activation of GABAA-receptor chloride channels,” Nature, vol. 341, no. 6239, pp. 233–236, 1989.
[4] M. Braun, R. Ramracheya, M. Bengtsson et al., “γ-Aminobutyric acid (GABA) is an autocrine excitatory transmitter in human pancreatic β-cells,” Diabetes, vol. 59, no. 7, pp. 1694–1701, 2010.
[5] A. Reetz, M. Solimena, M. Matteoli, F. Folli, K. Takei, and P. De Camilli, “GABA and pancreatic beta-cells: colocalization of glutamic acid decarboxylase (GAD) and GABA with synaptic-like microvesicles suggests their role in GABA storage and secretion,” The EMBO Journal, vol. 10, no. 5, pp. 1275–1284, 1991.
Glucose inhibition of GABA receptors and GABAergic signaling in pancreatic beta cells

GABA promotes human beta-cell proliferation and modulates glucose homeostasis, Diabetes, vol. 63, no. 9, pp. 4197–4205, 2014.

Combined antigen-based therapy with GABA treatment synergistically prolongs survival of transplanted beta-cells in diabetic NOD mice, PLoS One, vol. 6, no. 9, article e25337, 2011.

M. Braun, A. Wendt, K. Buschard et al., “GABAB receptor activation inhibits exocytosis in rat pancreatic beta-cells by G-protein-dependent activation of calcineurin,” The Journal of Physiology, vol. 559, Part 2, pp. 397–409, 2004.

A. Wendt, B. Birnir, K. Buschard et al., “Glucose inhibition of glucagon secretion from rat alpha-cells is mediated by GABA released from neighboring beta-cells,” Diabetes, vol. 53, no. 4, pp. 1038–1045, 2004.

M. Braun, A. Wendt, B. Birnir et al., “Regulated exocytosis of GABA-containing synaptic-like microvesicles in pancreatic beta-cells,” The Journal of General Physiology, vol. 123, no. 3, pp. 191–204, 2004.

J. Taneera, Z. Jin, Y. Jin et al., “γ-Aminobutyric acid (GABA) signalling in human pancreatic islets is altered in type 2 diabetes,” Diabetologia, vol. 55, no. 7, pp. 1985–1994, 2012.

R. W. Olsen and A. J. Tobin, “Metabotropic glucosensitive and GABA(B) receptors,” Physiological Reviews, vol. 84, no. 3, pp. 835–867, 2004.

B. Ligon, J. Yang, S. B. Morin, M. F. Ruberti, and M. L. Steer, “Regulation of pancreatic islet cell survival and replication by γ-aminobutyric acid,” Diabetologia, vol. 50, no. 4, pp. 764–773, 2007.

N. Soltani, H. Qiu, M. Aleksic et al., “GABA exerts protective and regenerative effects on islet beta cells and reverses diabetes,” Proceedings of the National Academy of Sciences of the United States of America, vol. 108, no. 28, pp. 11692–11697, 2011.

J. Tian, H. Dang, Z. Chen et al., “γ-Aminobutyric acid regulates both the survival and replication of human beta-cells,” Diabetes, vol. 62, no. 11, pp. 3760–3765, 2013.

G. J. Prud’homme, Y. Glinka, C. Hasilo, S. Paraskevas, X. Li, and Q. Wang, “GABA protects human islet cells against the deleterious effects of immunosuppressive drugs and exerts immunomodulatory effects alone,” Transplantation, vol. 96, no. 7, pp. 616–623, 2013.

I. Purwana, J. Zheng, X. Li et al., “GABA promotes human beta-cell proliferation and modulates glucose homeostasis,” Diabetes, vol. 63, no. 12, pp. 4197–4205, 2014.

J. Tian, H. Dang, B. Middleton, and D. L. Kaufman, “Clinically applicable GABA receptor positive allosteric modulators promote beta-cell replication,” Scientific Reports, vol. 7, no. 1, p. 374, 2017.

J. Tian, H. Dang, A. V. Nguyen, Z. Chen, and D. L. Kaufman, “Combined therapy with GABA and proinsulin/alum acts synergistically to restore long-term normoglycemia by modulating T-cell autoimmunity and promoting beta-cell replication in newly diabetic NOD mice,” Diabetes, vol. 63, no. 9, pp. 3128–3134, 2014.

J. Tian, H. Dang, and D. L. Kaufman, “Combining antigen-based therapy with GABA treatment synergistically prolongs survival of transplanted beta-cells in diabetic NOD mice,” JAMA, vol. 306, no. 22, pp. 2553–2554, 2011.

M. Braun, A. Wendt, K. Buschard et al., “GABA receptor activation inhibits exocytosis in rat pancreatic beta-cells by G-protein-dependent activation of calcineurin,” The Journal of Physiology, vol. 559, Part 2, pp. 397–409, 2004.

A. Wendt, B. Birnir, K. Buschard et al., “Glucose inhibition of glucagon secretion from rat alpha-cells is mediated by GABA released from neighboring beta-cells,” Diabetes, vol. 53, no. 4, pp. 1038–1045, 2004.

N. L. Brice, A. Varadi, S. J. Ashcroft, and E. Molnar, “Metabotropic glutamate and GABA(B) receptors contribute to the modulation of glucose-stimulated insulin secretion in pancreatic beta-cells,” Diabetologia, vol. 45, no. 2, pp. 242–252, 2002.
[36] A. M. Davalli, Y. Ogawa, C. Ricordi, D. W. Scharp, S. Bonner-Weir, and G. C. Weir, "A selective decrease in the beta cell mass of human islets transplanted into diabetic nude mice," *Transplantation*, vol. 59, no. 6, pp. 817–820, 1995.

[37] B. E. Gregg, P. C. Moore, D. Demozay et al., "Formation of a human β-cell population within pancreatic islets is set early in life," *The Journal of Clinical Endocrinology and Metabolism*, vol. 97, no. 9, pp. 3197–3206, 2012.

[38] S. Huang, J. Mao, B. Wei, and G. Pei, "The anti-spasticity drug baclofen alleviates collagen-induced arthritis and regulates dendritic cells," *Journal of Cellular Physiology*, vol. 230, no. 7, pp. 1438–1447, 2015.

[39] B. Duthey, A. Hubner, S. Diehl, S. Boehncke, J. Pfeffer, and W. H. Boehncke, "Anti-inflammatory effects of the GABA(B) receptor agonist baclofen in allergic contact dermatitis," *Experimental Dermatology*, vol. 19, no. 7, pp. 661–666, 2010.
