

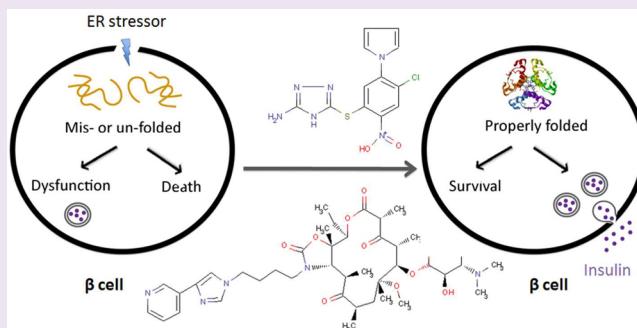
Identification of Small Molecules That Protect Pancreatic β Cells against Endoplasmic Reticulum Stress-Induced Cell Death

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 Supporting Information

ABSTRACT: Endoplasmic reticulum (ER) stress plays an important role in the decline in pancreatic β cell function and mass observed in type 2 diabetes. Here, we developed a novel β cell-based high-throughput screening assay to identify small molecules that protect β cells against ER stress-induced cell death. Mouse β TC6 cells were treated with the ER stressor tunicamycin to induce ER stress, and cell death was measured as a reduction in cellular ATP. A collection of 17600 compounds was screened for molecules that promote β cell survival. Of the approximately 80 positive hits, two selected compounds were able to increase the survival of human primary β cells and rodent β cell lines subjected to ER stressors including palmitate, a free fatty acid of pathological relevance to diabetes. These compounds also restored ER stress-impaired glucose-stimulated insulin secretion responses. We show that the compounds promote β cell survival by reducing the expression of key genes of the unfolded protein response and apoptosis, thus alleviating ER stress. Identification of small molecules that prevent ER stress-induced β cell dysfunction and death may provide a new modality for the treatment of diabetes.



Type 2 diabetes (T2D) is associated with pancreatic β cell dysfunction and death,¹ and increasing evidence indicates that endoplasmic reticulum (ER) stress is a major underlying cause of this decline.² ER stress has also been implicated in type 1 diabetes and monogenic diabetes.³ Thus, compounds that prevent ER stress-induced β cell death hold promise as potential therapeutic agents for diabetes.

Accumulation of misfolded or unfolded proteins in the ER induces activation of the unfolded protein response (UPR). This process is initiated by three ER membrane-associated proteins that act as unfolded protein sensors; IRE1 α , PERK, and ATF6, which each set in motion a series of events aimed at restoring ER homeostasis by altering the translation, folding, and post-translational modification of secreted and membrane proteins.⁴ If the three branches of the UPR fail to adequately compensate for the accumulation of aberrantly folded proteins, proapoptotic signals are triggered that ultimately lead to cell death.^{5,6}

Recent work has indicated that activation of the different branches of the UPR may be tissue- or cell type-specific and that the response to ER stress can result in survival or death depending on the cell type.^{7–9} Indeed, this is supported by high-throughput screening (HTS) studies identifying small molecules that inhibit ER stress in one cell type but not in others.^{10,11} For example, benzodiazepinone modulators of ASK1, a component of the IRE1 α branch of the UPR, were found to protect cultured neuronal cells against ER stress-induced apoptosis but paradoxically to potentiate ER stress-induced death of Jurkat cells (T leukemia line) and undifferentiated PC12 cells (pheochromocytoma line).¹¹ Likewise, salubrinal, which inhibits dephosphor-

ylation of eIF2 α (a PERK target), protects neuronal cells and PC12 cells from ER stress but triggers apoptosis in pancreatic β cells.^{10,12,13} These findings illustrate the cell-specific cytoprotective effects of ER stress-modulating compounds and emphasize the importance of screening for compounds on the specific cell type of interest.

In response to postprandial increase in blood glucose levels, β cells must produce and rapidly secrete insulin. To achieve this, they maintain a very large pool of proinsulin mRNA (~20% of the total cellular mRNA) and can increase proinsulin protein synthesis 25-fold upon glucose stimulation.^{14,15} This surge in proinsulin synthesis places a heavy burden on the protein-folding capacity of the ER, and as such, β cells are particularly susceptible to changes in ER homeostasis. These unique features of β cells may in part explain why compounds that protect many cell types from ER stress fail to protect β cells.^{12,13}

In this study, we sought to identify novel small molecules that protect pancreatic β cells from ER stress-induced dysfunction and death. To this end, we established a HTS assay in which a β cell line is subjected to chronic ER stress with tunicamycin (Tm), which inhibits N-linked glycosylation and causes the accumulation of misfolded proteins.¹⁶ We tested the ability of 17600 diverse compounds to promote β cell survival in this assay. Several hits were identified, validated, and further investigated by

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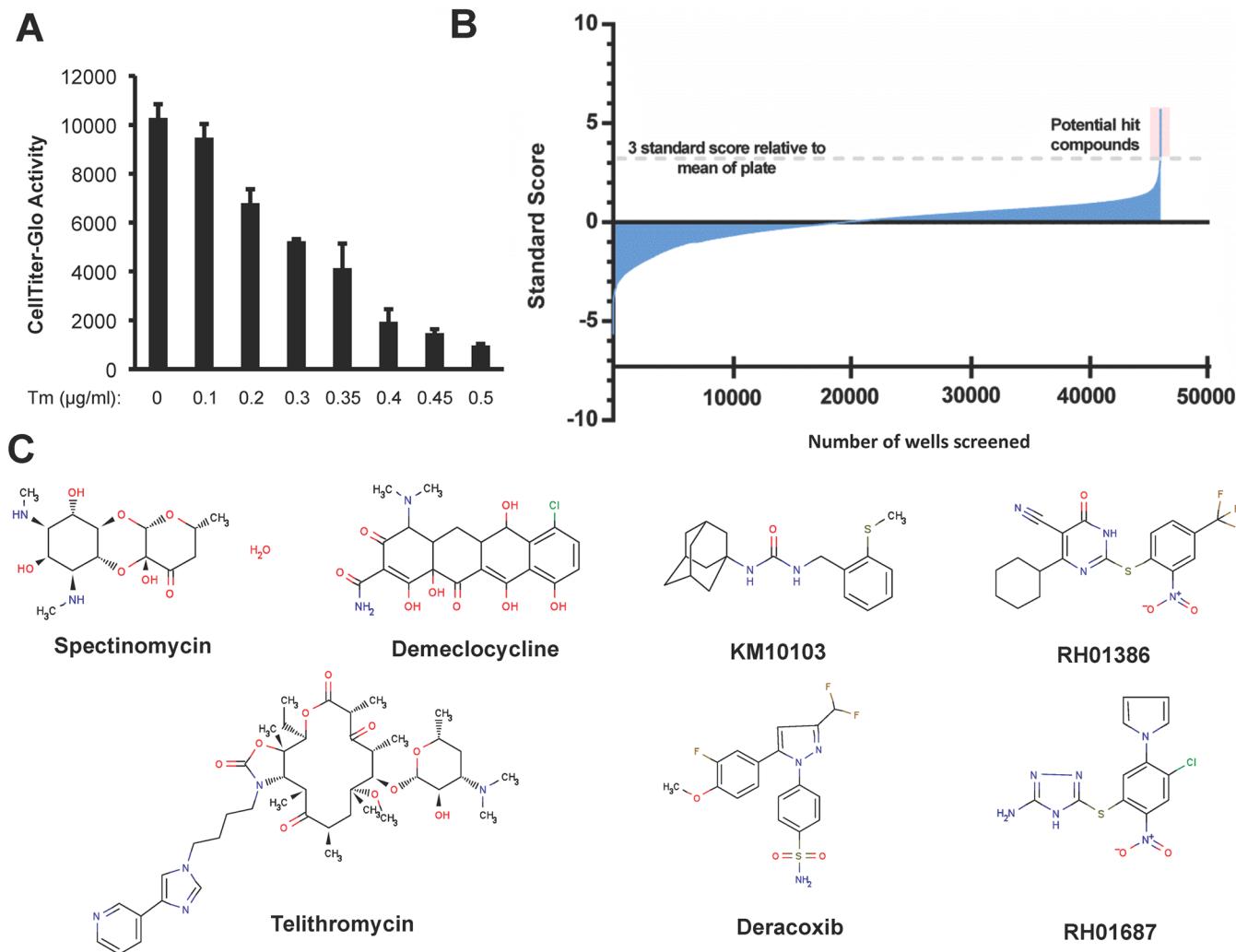


Figure 1. High-throughput screen for compounds that protect β cells against ER stress-induced death. (A) Cellular ATP levels (CellTiter-Glo luciferase activity) of mouse β TC6 cells treated with 0.1% DMSO (control) or varying concentrations of tunicamycin (Tm) for 72 h. Results are the mean \pm SD of four replicate wells and representative of three independent experiments. (B) Identification of hit compounds. For the DMSO control and test compound wells, the corrected mean \pm SD luminescence signal of 24 replicate wells was calculated. Standard score was calculated as (raw measurement of a compound – mean)/SD of the plate. Compounds were considered hits if they increased ATP levels >3 standard deviations compared with control wells containing Tm + DMSO. (C) Chemical structures of the seven hit compounds.

examining their effects on multiple β cell lines and primary human β cells treated with various chemical and pathophysiological ER stressors. These compounds not only promoted β cell survival but also restored the glucose-stimulated insulin secretion (GSIS) response in the presence of Tm. Finally, we demonstrate that these compounds protect β cells by inhibiting the expression of ER stress-associated and proapoptotic genes through distinct mechanisms. These results suggest that small molecule inhibitors of ER stress-induced β cell death may have therapeutic potential for diabetes.

RESULTS AND DISCUSSION

A Chronic β Cell ER Stress Assay for High-Throughput Screening. In T2D, β cells are under chronic ER stress induced by glucotoxicity, lipotoxicity, and amyloid accumulation due to obesity and insulin resistance.¹⁷ To identify compounds that protect β cells under conditions that mimic chronic ER stress, we developed a cell-based HTS assay in which the mouse insulinoma β cell line β TC6 is treated with Tm for 72 h, which induces characteristics of chronic ER stress.^{18,19} The cell viability is

quantified using a luminescent ATP assay amenable to HTS. We first established the optimal dose of Tm for reduction of intracellular ATP levels as an indication of ER stress-induced β cell death. Tm at 0.35 $\mu\text{g}/\text{mL}$ reduced cellular ATP levels by 50% compared with DMSO treatment (Figure 1A). This Tm concentration was therefore selected for our primary screen because it provides a sufficiently large window to observe inhibition of cell death by any protective compounds in the screening assay. The final assay was robust and highly reproducible, with a coefficient of variation (% CV) of 7.83% and a Z' factor of 0.74, using cells incubated with Tm and the vehicle DMSO as the positive control.

Identification of Compounds That Protect β Cells against ER Stress. We screened approximately 17600 compounds from several libraries, including the Microsource Spectrum Diverse Set (2320 bioactive compounds), NIH Clinical Collection (NCC; 840 bioactive compounds), and Maybridge Hitfinder collection (14400 compounds). Compounds were considered hits if they increased intracellular ATP levels by at least three standard deviations greater than the mean

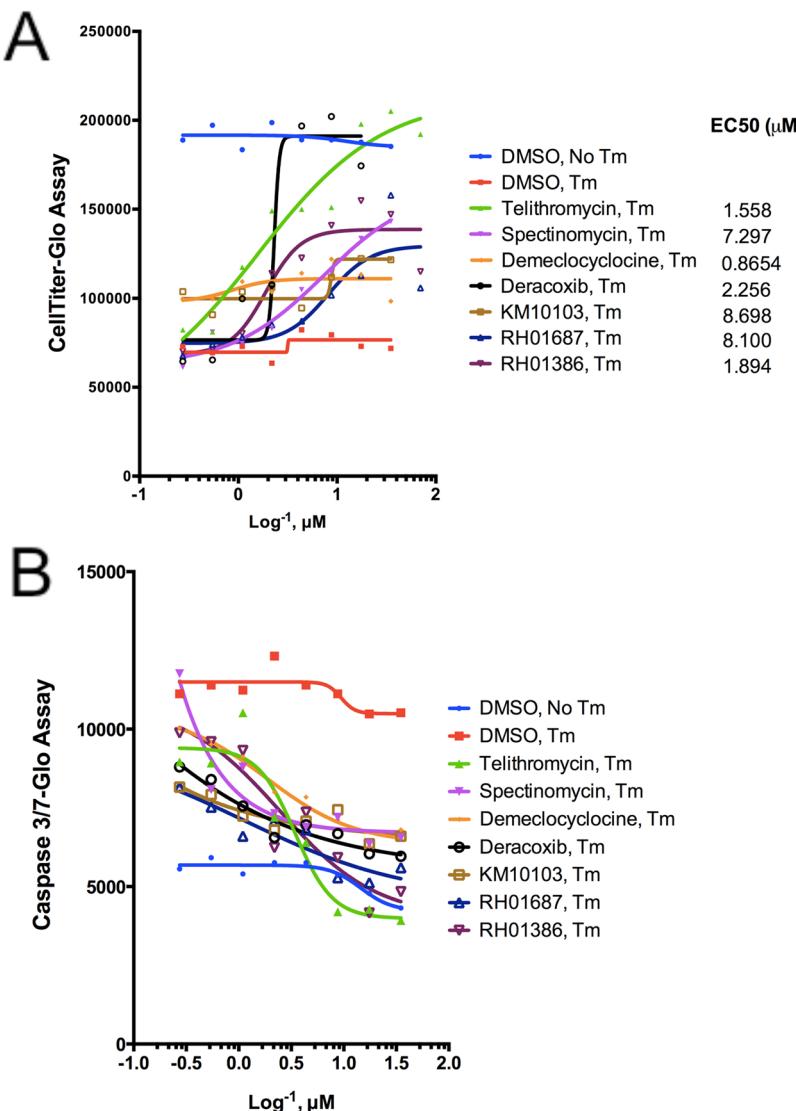


Figure 2. Hit compounds inhibit ER stress-induced death of β TC6 cells in a dose-dependent manner. (A, B) Cellular ATP levels (A) or caspase-3/7 levels (B) of β TC6 cells treated with 0.1% DMSO, Tm (0.35 μ g/mL), or Tm (0.35 μ g/mL) in the presence of the indicated concentrations of compounds for 72 h. EC₅₀ for each compound was calculated with GraphPad PRISM. Results are the mean of four replicate wells (with SD not shown for graphical simplicity) and representative of three independent experiments.

of control cells treated with Tm and DMSO. We identified 85 hits using this criterion (Figure 1B). Among the most potent hits in the Microsource and NCC collections were the antibiotics telithromycin, demeclocycline, and spectinomycin, as well as the cyclooxygenase-2 inhibitor deracoxib (Figure 1C). Hits from the Maybridge collection included compounds KM10103, RH01687, and RH01386 (Figure 1C). Each of these compounds was tested in more extensive dose–response assays with 2-fold dilutions between 70 μ M and 270 nM and confirmed to increase ATP levels in β TC6 cells treated with Tm (Figure 2A). These compounds were therefore selected for further study.

To rule out the possibility that the observed increases in cellular ATP levels were due to an increase in β TC6 cell proliferation, we incubated the cells for 7 days in the presence of the compounds alone. We observed no differences in the proliferation of cells treated with the compounds compared with control DMSO-treated cells, indicating that the increase in cellular ATP levels under ER stress reflects rescue of Tm-induced cell death rather than increased cell proliferation (Supporting Information, Figure S1). To confirm this, we measured the

effects of the seven compounds on the activity of caspase-3, a downstream effector of the apoptotic pathway. As expected, caspase-3 activity in β TC6 cells was markedly increased by Tm treatment, but all seven compounds dose-dependently inhibited the activity (Figure 2B). We conclude that these hits protect β TC6 cells from Tm-induced cell death.

Hit Compounds Inhibit ER Stress-Induced Death of Primary Human β Cells. The primary screen and confirmatory assays were performed with the β TC6 mouse β cell line. Therefore, we next asked whether the hit compounds have similar effects on additional β cell lines and, most importantly, on primary human β cells. Indeed, Tm-induced death of mouse (MIN6) and rat (INS-1) β cell lines was inhibited by the majority of compounds, although there were some differences between the cell lines in their sensitivity to some compounds (Figure 3A,B, respectively). Next, we examined the compounds' effects on primary human islets and observed that telithromycin, spectinomycin, KM10103, RH01386, and RH01687 all significantly inhibited Tm-induced cell death, as indicated by the marked reduction of terminal deoxynucleotidyl transferase

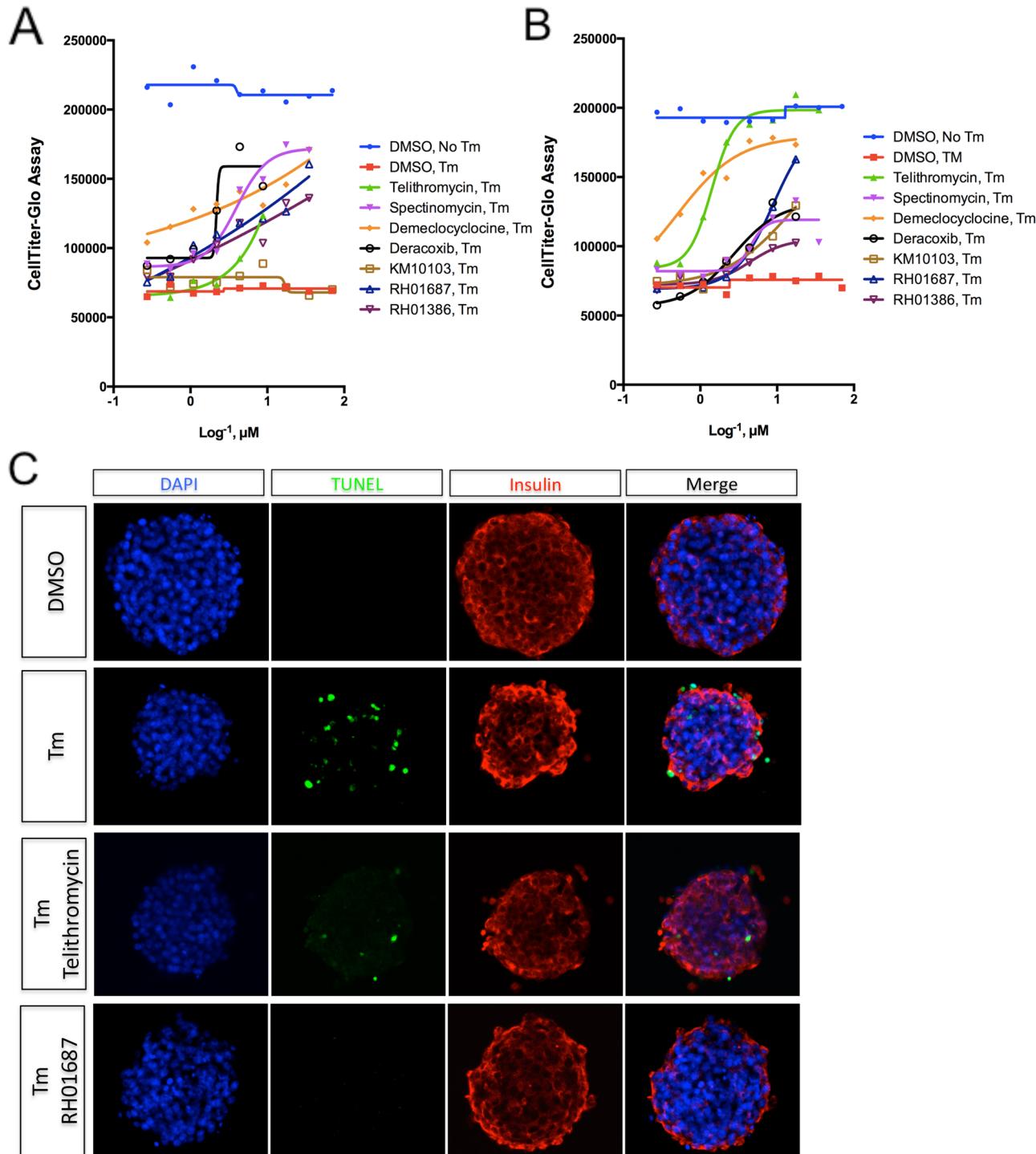


Figure 3. Hit compounds protect primary human β cells and rodent β cell lines against ER stress-induced death. (A, B) Cellular ATP levels of mouse MIN6 (A) and rat INS-1 (B) β cells treated with 0.5 and 0.17 μ g/mL Tm, respectively, and the indicated compounds for 72 h. Results are the mean of four replicate wells (with SD not shown for graphical simplicity) and representative of three independent experiments. (C) TUNEL staining in primary human islets. Primary human islets were treated with 0.75 μ g/mL Tm and 20 μ M of the indicated compounds for 72 h before TUNEL staining. Anti-insulin antibody was used to mark insulin $^{+}$ β cells, and DAPI was used as a nuclear marker. Tm treatment induced TUNEL staining, which was mitigated or abolished by hit compound treatment.

dUTP nick end labeling (TUNEL) staining (a marker for cell death) in compound-treated insulin $^{+}$ β cells compared with DMSO-treated counterparts (Figure 3C and Supporting Information, Figure S2). These results indicate that the majority of the hit compounds are active in protecting rodent β cell lines and human primary β cells against ER stress.

Hit Compounds Protect against the Effects of Pathophysiological ER Stressors. ER stress can be induced by a number of stimuli acting through distinct molecular mechanisms. We therefore investigated the cytoprotective effects of the compounds when β TC6 cells were treated with thapsigargin (Tg) and brefeldin A (BFA), two commonly used

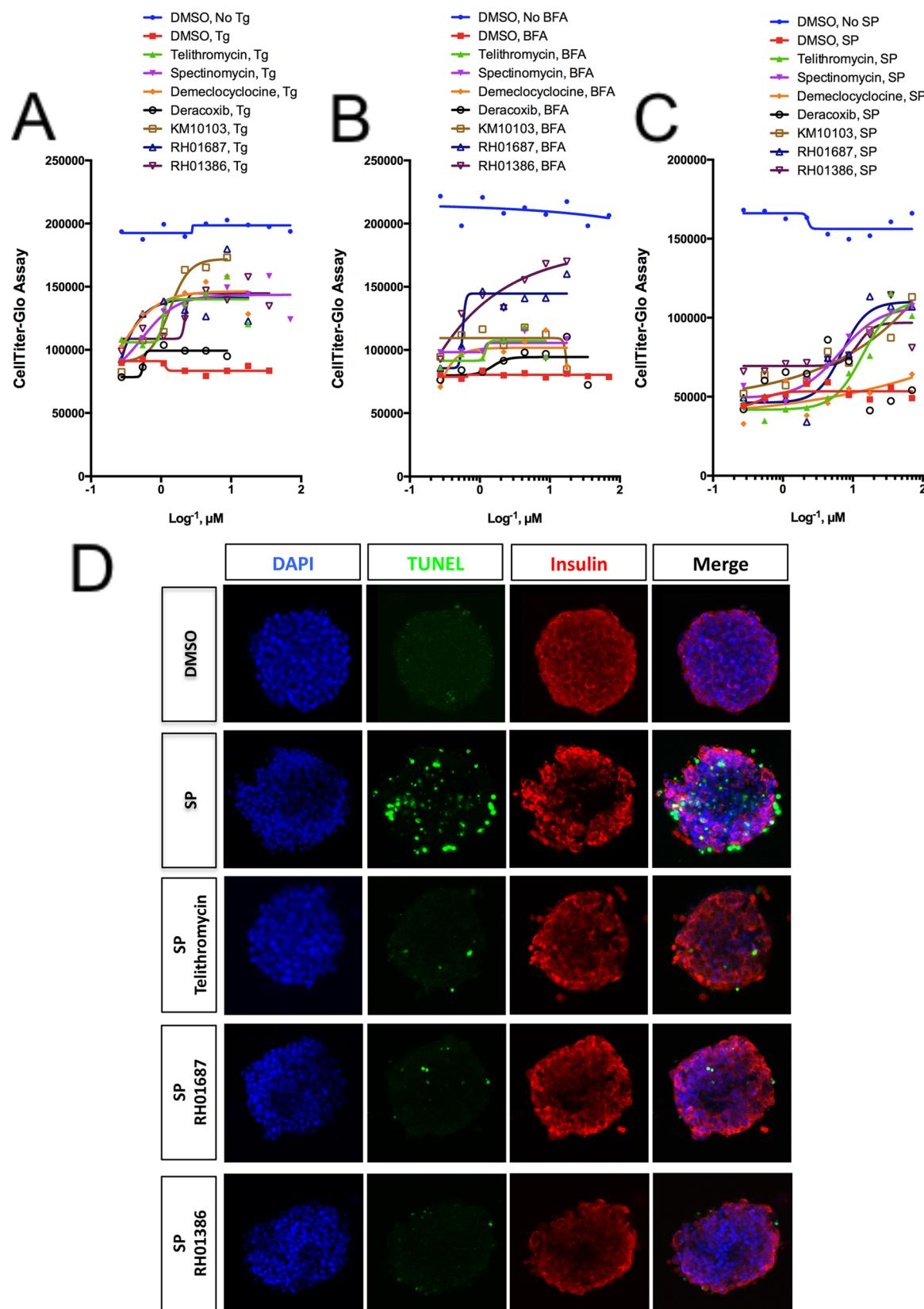


Figure 4. Protective effect of hit compounds on β cell death induced by thapsigargin, brefeldin A, and palmitate. (A–C) Cellular ATP levels of β TC6 cells treated with the indicated compounds in the presence of 0.05 μ M thapsigargin (Tg; A), 0.2 μ g/mL brefeldin A (BFA; B), or 0.7 mM sodium palmitate (SP)/BSA conjugate (C) for 72 h. Results are the mean of four replicate wells (with SD not shown for graphical simplicity) and representative of three independent experiments. (D) TUNEL staining in primary human islets. Primary human islets were treated with 20 μ M of the indicated compounds and 0.75 mM SP/BSA for 72 h before TUNEL staining. Anti-insulin antibody was used to mark insulin $^+$ β cells, and DAPI was used as a nuclear marker. SP treatment induced TUNEL staining, which was mitigated or abolished by hit compound treatment.

agents to induce ER stress. Tg induces ER stress by inhibiting sarcoplasmic/endoplasmic reticulum Ca^{2+} -ATPase (SERCA), which disrupts intraluminal Ca^{2+} homeostasis in the ER and causes accumulation of unfolded proteins.¹⁶ BFA inhibits a key guanine nucleotide exchange factor essential for the transport of proteins from the ER to the Golgi.¹⁶ We observed that β TC6 cell death induced by Tg was inhibited by all selected hit compounds except deracoxib (Figure 4A), whereas BFA-induced death was inhibited significantly by RH01687 and RH01386 as well as by other hit compounds to a lesser extent (Figure 4B). Thus, the compounds were effective in reducing cell death induced by the three ER stressors, but the results suggest that the compounds show some cell type and stressor specificity.

We then investigated whether the hit compounds can protect β TC6 cells against a pathologically relevant ER stressor, the long-chain saturated free fatty acid (FFA) palmitate. Free fatty acids are thought to be important physiological mediators of β cell dysfunction and death in T2D, and palmitate has previously been shown to induce ER stress-mediated death of β cells.²⁰ We found that palmitate-induced death of β TC6 cells was reduced by treatment with telithromycin, spectinomycin, KM10103, RH01687, and RH01386 (Figure 4C). Likewise, death of primary human β cells induced by palmitate was rescued by telithromycin, RH01687, and RH01386 (Figure 4D).

Taken together, these observations demonstrate that the hit compounds can reduce ER stress-related cell death of rat and murine β cell lines and primary human β cells induced by four ER stressors: Tm, Tg, BFA, and palmitate. Notably, the compounds show varying degrees of protection depending on both the β cell type and the ER stressor. This might be explained in part by the differing sites of action of the ER stressors. For example, in addition to inducing ER stress, Tg induces autophagy and BFA disrupts Golgi function. Nevertheless, compounds RH01687 and RH01386 effectively reduced death of rodent β cell lines and primary human β cells induced by all four ER stressors tested, including the pathologically relevant stressor palmitate. Interestingly, RH01687 and RH01386 are structurally similar, both having core nitrogen-containing aromatic rings linked with the 2-nitro-phenylthio group (Figure 1C). We selected RH01687 and telithromycin (as a representative of antibiotics) for further mechanistic analyses.

Cytoprotective Compounds Preserve the Insulin-Secreting Function of β Cells. Secretory cells are particularly vulnerable to agents that disrupt protein translation, folding, and modification. As a result, ER stress directly impairs β cell function, including insulin biosynthesis and GSIS.^{21,22} We next examined whether our hit compounds could re-establish GSIS in β cells treated with Tm. Incubation of INS-1 cells in 25 mM glucose-containing medium increased insulin secretion approximately 2-fold compared with baseline secretion in 2.8 mM glucose medium (Figure 5A). Tm treatment not only abolished insulin secretion stimulated by high glucose concentrations but also reduced basal levels of insulin secretion, consistent with disruption of ER homeostasis (Figure 5A). Addition of RH01687 or telithromycin significantly increased GSIS in the Tm-treated cells and also increased basal levels of secretion, although the latter did not reach the level of statistical significance. We also examined the GSIS response of primary human islets and found that RH01687 and telithromycin were also able to significantly restore the Tm-inhibited GSIS response of these cells (Figure 5B). Thus, RH01687 and telithromycin not only protect β cells against ER stress-induced cell death but also preserve β cell function.

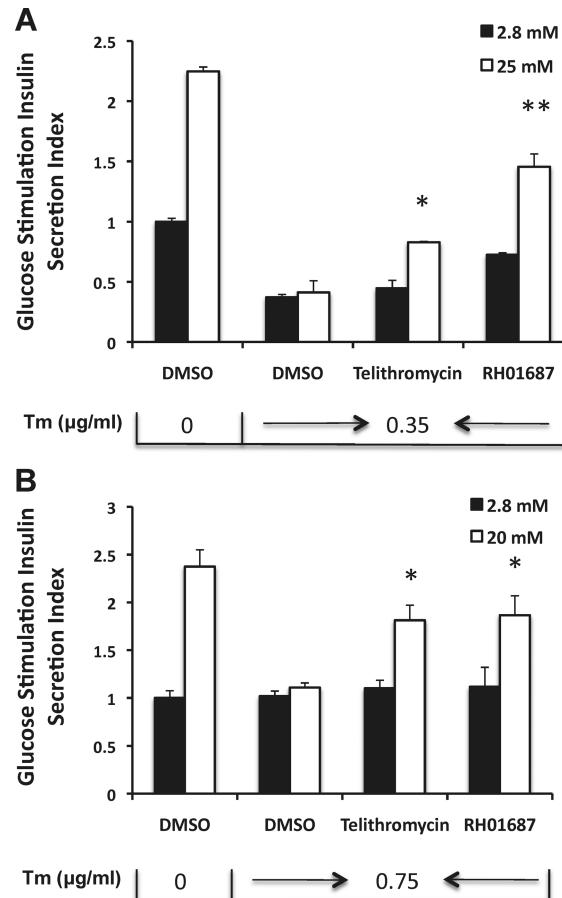


Figure 5. Hit compounds preserve glucose-stimulated insulin secretion in β cells subjected to ER stress. (A) Insulin secretion by INS-1 cells incubated with 2.8 mM or 25 mM glucose in the presence of 0.35 $\mu\text{g}/\text{mL}$ Tm and the indicated compounds. Secreted insulin was measured by ELISA after 72 h incubation, and the values were normalized to total cellular protein. (B) Insulin secretion by human islets (50 of equal size) incubated with 2.8 mM glucose or 20 mM glucose in the presence of 0.75 $\mu\text{g}/\text{mL}$ Tm and the indicated compounds. Secreted insulin was measured by ELISA after 72 h incubation, and the values were normalized to total islet protein. For both panels A and B, data are shown as glucose stimulation insulin secretion index (= mean of secreted insulin from quadruple wells incubated with 25 mM (for INS-1) or 20 mM (for human islets) glucose/mean of secreted insulin from quadruple wells incubated with 2.8 mM glucose), in which the baseline insulin secretion at 2.8 mM glucose was normalized as 1, and were representative of four independent experiments. * $P < 0.05$, ** $P < 0.001$ by Student's *t*-test compared with control cells treated DMSO + Tm.

Cytoprotective Compounds Protect β Cells by Alleviating ER Stress and Inhibiting Proapoptotic Gene Expression. We next investigated the molecular mechanisms by which the hit compounds exert their protective effects. First we wanted to determine whether our hit compounds protect β cell survival by resolving or alleviating ER stress. ER stress induces the UPR signaling pathways of IRE1 α , PERK, and ATF6 α , which trigger translational and transcriptional changes aimed at re-establishing ER homeostasis. Failure to resolve or adequately control ER stress can result in UPR-triggered apoptosis. The C/EBP-homologous protein (CHOP) is a transcription factor that is activated during ER stress-triggered apoptosis; it is induced under ER stress mainly by the PERK pathway, although IRE1 α and ATF6 α also contribute,^{23,24} and is generally used as an ER stress marker of apoptosis.²⁵ As expected,

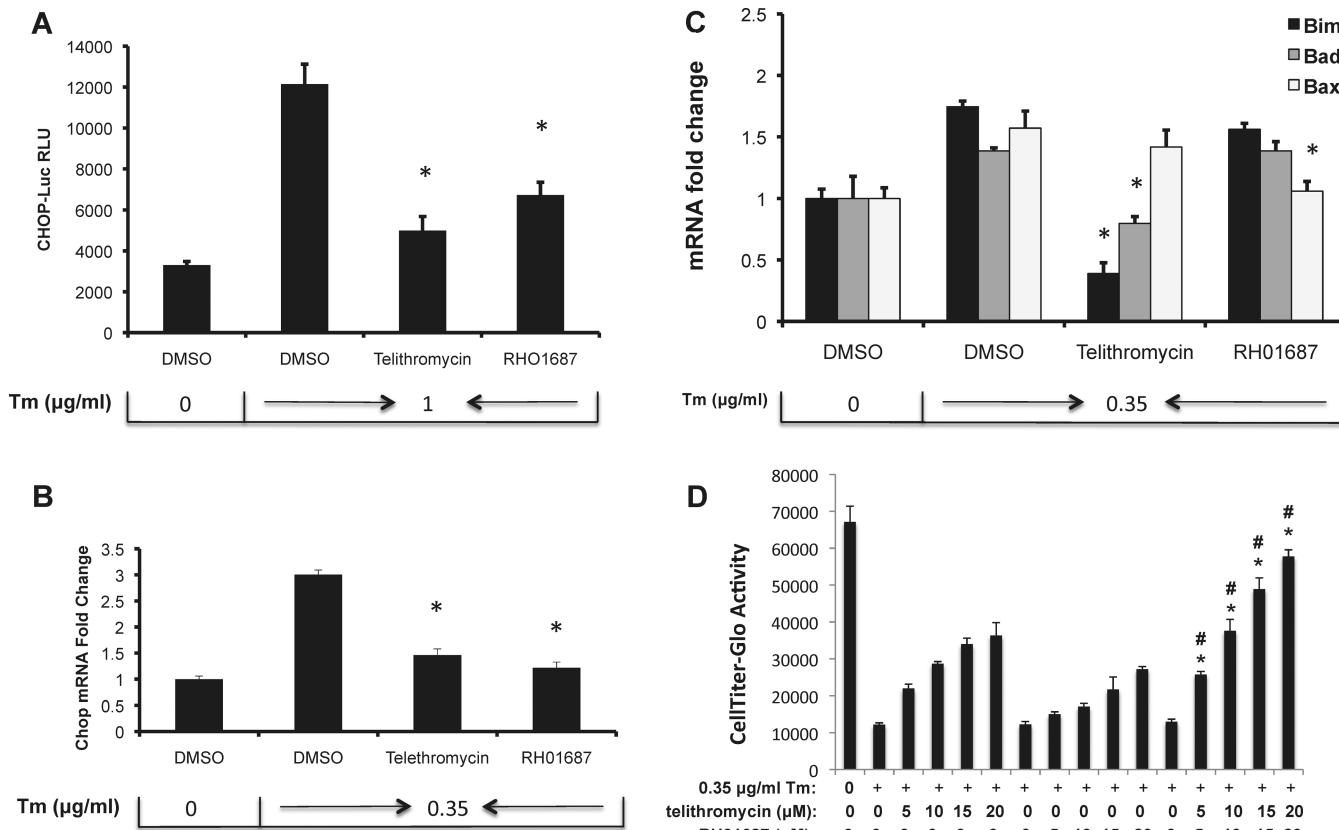


Figure 6. Hit compounds inhibit ER stress-induced expression of CHOP and proapoptotic genes. (A) HEK293 cells stably transfected with a CHOP promoter/Luciferase reporter construct were treated with 1 μ g/mL Tm and 20 μ M of the indicated compounds for 24 h before luciferase activity was measured. Results are the mean \pm SD of $n = 8$ wells and representative of four independent experiments. * $P < 0.05$ by Student's *t*-test compared with control cells treated with DMSO + Tm. (B, C) qRT-PCR analysis of mRNA levels of CHOP (B) or the proapoptotic genes Bim, Bad, and Bax (C) in β TC6 cells treated with 0.35 μ g/mL Tm and the indicated compounds for 24 h. mRNA levels were normalized to *Gapdh* mRNA and are expressed as the fold increase in mRNA compared with cells treated with DMSO alone. Results are the mean \pm SD of $n = 3$ wells and representative of four independent experiments. * $P < 0.05$ by Student's *t*-test compared with Tm-treated cells. (D) Additive effect of telithromycin and RH01687 on Tm-induced β TC6 cell death. β TC6 cells were treated with 0.35 μ g/mL Tm and the indicated concentrations of telithromycin or RH01687, either alone or in combination, for 72 h before measurement of cellular ATP levels. * $P < 0.05$ by Student's *t*-test compared with the same concentrations of telithromycin alone, and # $P < 0.05$ by Student's *t*-test compared with the same concentration of RH01687 alone.

Tm significantly induces the expression of CHOP as shown in Figure 6A,B. To determine whether CHOP expression is affected by the hit compounds, we used HEK293 cells stably transfected with a CHOP promoter/luciferase reporter construct that faithfully reflects endogenous CHOP gene expression.²⁶ Tm treatment of these cells induced the luciferase reporter by ~3-fold, but treatment with RH01687 or telithromycin significantly inhibited CHOP expression (Figure 6A). To confirm this in β cells, we analyzed CHOP mRNA expression in β TC6 cells by qPCR; indeed, RH01687 and telithromycin both significantly suppressed the Tm-induced CHOP mRNA level increases in these cells (Figure 6B). These results indicate that the hit compounds protect β cell survival by alleviating ER stress.

We then investigated whether our hit compounds affect the expression levels of proapoptotic genes. Under unresolved ER stress, multiple factors, CHOP, ATF4, P53, and JNK, have been reported to be induced to participate in the induction of proapoptotic BH3-only proteins such as Bim, Bad, Noxa, and Puma.^{27,28} Each BH3-only protein is activated by ER stress in a distinct manner. For example, Bim is activated by CHOP and JNK, whereas Puma and Noxa are activated by ER stress-mediated p53 up-regulation. These BH3-only proteins subsequently stimulate the multidomain proapoptotic proteins Bax

or Bak to form homo-oligomers in the outer mitochondrial membrane, leading to caspase-mediated cell death. We examined expression of Bim, Bad, and Bax mRNA in β TC6 cells. Treatment with Tm for 24 h significantly increased the expression of each gene (Figure 6C), but interestingly telithromycin and RH01687 had qualitatively and quantitatively different effects. Telithromycin significantly decreased the levels of Bim and Bad mRNAs but not of Bax mRNA (Figure 6C). On the other hand, RH01687 attenuated the Tm-induced increase of Bax mRNA but not of Bim or Bad mRNA (Figure 6C). These results suggest that, although both compounds alleviate ER stress to protect β cells, they appear to do so by targeting different UPR pathways (Figure 6C).

We further asked whether the combination of these two compounds might have an additive effect in protecting β TC6 cells from Tm-induced cell death. Indeed, cells treated with Tm and both telithromycin and RH01687 at varying concentrations showed significantly increased survival compared with cells treated with the same concentrations of either compound alone (Figure 6D). These results indicate that the two compounds inhibit ER stress-induced β TC6 death in an additive manner, consistent with their distinct effects on Bim and Bax expression.

Telithromycin Inhibits ATF4- and CHOP-Induced Protein Synthesis Increase under ER Stress. Several of our hit compounds including telithromycin belong to a class of bacteriostatic antibiotics that primarily block prokaryotic protein synthesis by targeting ribosomes. However, some bacteriostatic antibiotics are just as effective in inhibiting eukaryotic protein synthesis.²⁹ We hypothesize that these antibiotic hits in our screen could protect β cells against ER stress-induced cell death by inhibiting protein translation. Increase in protein synthesis was recently reported to be one mechanism of ER stress-induced cell death.^{30–32} Under ER stress, phosphorylation of eIF2 α by PERK reduces overall protein translation to re-establish ER homeostasis; however, it also preferentially promotes the translation of several mRNAs containing 5'-upstream open reading frames such as ATF4, which subsequently induces the expression of CHOP. ATF4 and CHOP act together to activate the expression of genes involved in protein synthesis to restore general mRNA translation. The ATF4- and CHOP-mediated restoration of protein synthesis promotes cell survival after ER homeostasis is re-established when ER stress is transient. However, under severe or prolonged ER stress, in which the initial protein synthesis reduction fails to restore ER homeostasis, the ATF4- and CHOP-mediated protein synthesis increase leads to ATP depletion, oxidative stress, and cell death.^{30–32}

To determine whether telithromycin suppresses the ATF4- and CHOP-mediated mRNA translation increase in β cells, we measured the rate of protein synthesis of β TC6 cells under ER stress with and without telithromycin. Consistent with recent reports,^{30,31} Tm treatment led to an initial steep decline in protein synthesis, but it underwent a gradual recovery (Figure 7, lanes 1, 2, 4, 6, 8, 10, and 12). We observed that telithromycin attenuated the recovery of protein synthesis in Tm-treated β TC6 cells (Figure 7, lanes 3, 5, 7, 9, 11, and 13). These results suggest that telithromycin protects β cell survival against ER stress likely by inhibiting ATF4- and CHOP-mediated protein synthesis increase.

Discussion. In this study, we have described a novel HTS assay for the identification of small molecule inhibitors of ER stress-induced apoptosis in pancreatic β cells. Several compounds identified were able to protect primary human β cells from cell death induced by various ER stressors, including the diabetes-relevant free fatty acid palmitate. Notably, the compounds appeared to protect against ER stress by inhibiting the expression of key genes known to be involved in UPR-stimulated apoptosis.

Previous HTS efforts have identified compounds that modulate the UPR pathway in cell-free biochemical assays^{33–39} and that protect non- β cells against ER stress-induced death.^{10,11} We found that most of those compounds (e.g., salubrinal, STF083010, quercetin) were ineffective in protecting β cells against ER stress-induced cell death, and some compounds even potentiated β cell death (Supporting Information, Figure S2). These results are consistent with recent reports that salubrinal protects neuronal and PC12 cells from ER stress-related death but triggers apoptosis in β cells.^{12,13} These observations indicate that strategies aimed at alleviating ER stress-induced activation of the UPR and its outcome must be tailored to the cell type of interest.

Two of our hit compounds, telithromycin and RH01687, suppressed the expression of CHOP, an indicator of the ER stress response, suggesting that these compounds protect β cell survival by alleviating ER stress. Our subsequent findings that telithromycin and RH01687 have inverse effects on the

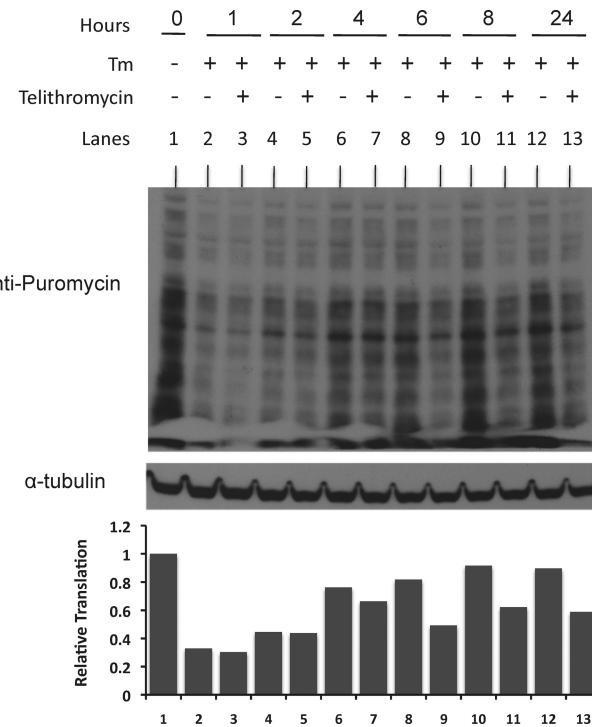


Figure 7. Telithromycin inhibits ATF4- and CHOP-induced protein synthesis increase under ER stress. Newly synthesized proteins were pulse-labeled with 5 μ g/mL puromycin for 10 min in β TC6 cells treated with Tm in the presence or absence of telithromycin (20 μ M) at specified time points. Puromycin-bound newly synthesized proteins were detected by immunoblotting with anti-puromycin antibody. The intensity of the total signal of each lane was measured with Image-J software and plotted under the image of the immunoblot with the relative intensity of the signal for the sample in the absence of Tm as 1. The data shown is a representative of three independent experiments.

proapoptotic factors Bim, Bad, and Bax indicate that the two compounds likely increase β cell survival by targeting different UPR branches or components. This notion is further supported by our observation that the combination of telithromycin and RH01687 had a greater effect on β cell survival than either compound alone. These findings also suggest that diseases caused by protein misfolding might benefit from combinatorial therapy that targets multiple arms of the UPR. While the identification of the cellular targets of RH01687 is currently underway, our results on telithromycin (Figure 7) indicate that it protects β cells from ER stress-induced death by attenuating ATF4- and CHOP-mediated protein translation increase. Several reports have shown that ER stress-induced activation of the transcription factor ATF4 and CHOP increases protein synthesis, which in turn causes ATP depletion, oxidative stress, and cell death.^{30–32} We observed that telithromycin attenuated the ATF4- and CHOP-mediated protein overproduction, without affecting insulin secretion in response to glucose stimulation (Figure 5). This could be achieved if β cells possess a mechanism to distinguish between the unwanted global protein overproduction and glucose-triggered β cell-intrinsic insulin production and secretion. Taken together, our work suggests that diseases involving aberrant protein folding may benefit from therapeutic agents that limit protein synthesis. Interestingly, in a screen for compounds that promote self-renewal of human embryonic stem cells, 18% of the confirmed hits were

antibiotics.⁴⁰ These and our findings may suggest a relationship between ER stress/protein synthesis and cell survival/growth.

Our study suggests that identification of compounds able to protect β cells against ER stress and elucidation of their mechanisms of actions may not only lead to the development of therapeutics for diabetes but also uncover novel players and mechanisms that are unique to the UPR and ER stress response in β cells.

METHODS

Cell Culture and Reagents. The mouse insulinoma cell lines β TC6 (ATCC) and MIN6 were maintained in Dulbecco's modified Eagle's medium (DMEM) supplemented with 15% fetal bovine serum (FBS), 1× GlutaMAX, 1× nonessential amino acids, and 1 mM sodium pyruvate. INS-1 rat insulinoma cells were maintained in RPMI medium supplemented with 10% FBS, 1× GlutaMAX, 1× nonessential amino acids, and 1 mM sodium pyruvate. Human islets were obtained from the Integrated Islet Distribution Program (Duarte, CA) in accordance with Oklahoma Medical Research Foundation internal review board (IRB) and ethical guidelines for the use of human tissue. Standard viability was 80–90% and purity was >80%. Islets were maintained in CMRL medium supplemented with 10% FBS. All cells were grown at 37 °C in a humidified 5% CO₂ atmosphere. Tunicamycin (Tm), brefeldin A (BFA), and thapsigargin (Tg) were from Sigma. CellTiter-Glo and Caspase-Glo 3/7 reagents were from Promega. Salubrinal, guanabenz acetate, STF083013, and kaempferol were from Tocris, quercentin and apigenin were from Cayman, and PP1 Analog II was from Calbiochem.

Compound Libraries. Three compound libraries were screened: 2320 compounds from Microsource Spectrum Diverse Set (Microsource Discovery Systems), 840 from the NIH Clinical Collection (NIH), and 14400 from Maybridge Hitfinder (Maybridge Corporation). All compounds were stored in DMSO at 10 mM. Compounds from the Microsource Spectrum and NIH Clinical Collection (NCC) were formatted in an 8-point 2-fold titration fashion, with high concentration at 10 mM.

High-Throughput Screening Assay. β TC6 cells were resuspended in DMEM/15% FBS and plated at 5×10^3 cells/(40 μ L·well) into white clear bottom 384-well plates (Greiner) using an automated liquid handler (Thermo Fischer Scientific). After 24 h incubation at 37 °C, library compounds were added to the wells at a final concentration of 10 μ M using a pin-transfer robot (PerkinElmer). Tm in DMEM/15% FBS was then added at a final concentration of 0.35 μ g/mL. Control wells contained β TC6 cells + Tm + 0.1% DMSO. After 72 h, the medium was removed and 20 μ L of CellTiter-Glo reagent was added. Luminescence was measured 10 min later using an Envision plate reader (PerkinElmer). Maybridge library was screened at single point (10 μ M), while Microsource and NCC libraries were screened at eight 2-fold serial points with highest concentration of 10 μ M.

Screening Data Analysis. Hit selection was based on "standard scores" (Figure 1B). The mean and standard deviation (SD) of luminescence for each compound was determined, and the standard score for each compound was then calculated as (raw measurement of a compound – mean)/SD of the plate. Compounds that increased ATP levels >3 standard deviations compared with control wells (standard score >3) were considered hits. Compounds identified from the primary screen were cherry picked into new 384-well plates in ten 2-fold serial concentration dilutions for validation experiments. The signal/noise ratio of the assay was determined from the mean and SD of the sample and background of the plate as previously described.⁴¹ The Z' factor of the assay was calculated from the means and SDs between DMSO-treated and Tm-treated wells, as previously described.⁴²

ATP and Caspase-3 Assays. Assays were performed as described for the HTS screening with the following exceptions. All cells were incubated in 384-well plates at 3×10^3 cells/(40 μ L·well) except human islet β cells, which were added at 10^5 cells/well. Final concentrations of test compounds above 10 μ M were obtained by repeated addition from the same stock plate of 10 mM compound. Final concentrations of Tm were 0.35 μ g/mL for β TC6, 0.5 μ g/mL for MIN6, 0.17 μ g/mL for INS1, and 0.75 μ g/mL for primary human islet cells. Final concentrations of

Tg and BFA were 0.05 μ M and 0.2 μ g/mL, respectively. For assays in which ER stress was induced by palmitate, a stock solution of 5 mM sodium palmitate (SP) in 5% BSA was prepared as previously reported.⁴³ The medium was changed to DMEM/1% FBS/1% BSA (final concentration, taking into account the SP/BSA addition), and SP was added to a final concentration of 0.7 mM. After 72 h incubation at 37 °C, the medium was removed, and cells were incubated with 20 μ L of CellTiter-Glo (for ATP levels) or Caspase-Glo 3/7 (for caspase-3 activity) reagents. Luminescence was measured after 10 min (CellTiter-Glo) or 2 h (Caspase-Glo 3/7).

CHOP Reporter Assay. HEK293 cells stably transfected with a CHOP promoter/luciferase reporter were plated at 7×10^3 cells/well in a 384-well plate and incubated for 16 h. Test compounds were then added, followed by Tm at 1 μ g/mL. Luciferase activity was measured with a Bright-Glo kit (Promega) 24 h later.

Glucose-Stimulated Insulin Secretion. INS-1 or primary human islet cells were plated at 1.5×10^4 /well in 96-well plates and incubated overnight. The following day, test compounds and 0.35 or 0.7 μ g/mL Tm were added for a further 72 h. Cells were washed and incubated for 2 h in freshly prepared KRBH buffer (115 mM NaCl, 5 mM KCl, 24 mM NaHCO₃, 2.5 mM CaCl₂, 1 mM MgCl₂, 10 mM HEPES, 2% w/v BSA, pH 7.4) containing 2.8 mM glucose. Cells were then incubated for an additional hour in KRBH buffer containing 2.8, 25 (for INS-1 cells), or 20 mM (for human islets) glucose. The supernatants were collected, and secreted insulin was measured using insulin ELISA kits (for mouse insulin from Millipore and for human insulin from LifeTech). Cells were lysed with RIPA buffer (50 mM Tris HCl pH 7.4, 1% NP-40, 0.25% sodium deoxycholate, 150 mM NaCl) containing protease inhibitors, and total cellular protein was determined with Bradford protein assay. All secreted insulin levels were corrected for total protein. Data were shown as glucose stimulation insulin secretion index (= [mean of secreted insulin from quadruple wells incubated with 25 mM (for INS-1) or 20 mM (for human islets)]/[mean of secreted insulin from quadruple wells incubated with 2.8 mM]).

Quantitative Real-Time PCR. RNA was isolated from β TC6 cells using TRIzol (Life Technologies) and reverse transcribed using oligo d(T) primers (New England Biosystems) and SuperScript III reverse transcription kit (Applied Biosystems). qPCR was performed using SYBR Green mix (Applied Biosystems) with an Applied Biosystems 7500 real-time PCR system. Mouse-specific primers were as follows: *Bax*, 5'-ACCAAGAACGCTGAGCGAGTGT-3' and 5'-CACGTCAGCAATCATCCTCT-3'; *Bad*, 5'-GGATGAGCGATGAGTTGAGG-3' and 5'-TCCCACCAGGACTGGATAATG-3'; *Bim*, 5'-CGACAGTCTCAGGAGGAACC-3' and 5'-CATTGCAAA-CACCCCTCCTT-3'; *Chop*, 5'-TTCACTACTCTTGACCCCTGCGTCT-3' and 5'-CACCTGACCACTCTGTCTTCT-3'; *Gapdh*, 5'-CCTGGAGAACCTGCCAAGTA-3' and 5'-TGGAAAGAGTGG-GAGTTGCTGT-3'. Relative mRNA levels were normalized against the housekeeping gene *Gapdh* using the comparative CT method.

Immunofluorescent and TUNEL Staining. Human islets were briefly washed with PBS and fixed with 4% paraformaldehyde for 30 min at RT. Fixed cells were blocked in 5% normal donkey serum for 30 min. Polyclonal guinea pig anti-insulin (A0564, Dako, 1:500 dilution) was used as primary antibody. Donkey Cy3 anti-guinea pig IgG was used as secondary antibody. Terminal deoxynucleotidyl transferase dUTP nick end labeling (TUNEL) staining was performed to detect apoptosis with In Situ Cell Death Detection Kit-Fluorescein (Cat. No. 11684795910, Roche), according to the manufacturer's instruction. DAPI was used for nuclear counter-staining. Images were taken with Olympus FV1000 confocal microscopy.

Measurement of Protein Synthesis with Puromycin Labeling Assay. β TC6 cells (5×10^5) treated with Tm in the presence or absence of telithromycin at specified time points were pulsed with 5 μ g/mL puromycin for 10 min to label newly synthesized proteins.⁴⁴ Cells were washed 3 times with ice-cold PBS followed by lysis with RIPA buffer supplemented with protease inhibitors, cleared by centrifugation, and analyzed by Western blotting with antipuromycin antibody (Millipore, MABE343, clone 12D10, 1:20000 dilution).

Statistical Analysis. Data are presented as means \pm SD. Comparisons were performed by two-tailed paired Student's *t*-test. A *P* value < 0.05 was considered statistically significant.

■ ASSOCIATED CONTENT

Supporting Information

Data showing that hit compounds do not increase β cell ATP levels by inducing cell proliferation, hit compounds protect human β cells against ER stress-induced death, and known modulators of ER stress do not protect β cells against ER stress. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

- (1) Prentki, M., and Nolan, C. J. (2006) Islet beta cell failure in type 2 diabetes. *J. Clin. Invest.* **116**, 1802–1812.
- (2) Fonseca, S. G., Gromada, J., and Urano, F. (2011) Endoplasmic reticulum stress and pancreatic beta-cell death. *Trends Endocrinol. Metab.* **22**, 266–274.
- (3) Eizirik, D. L., Cardozo, A. K., and Cnop, M. (2008) The role for endoplasmic reticulum stress in diabetes mellitus. *Endocr. Rev.* **29**, 42–61.
- (4) Schroder, M., and Kaufman, R. J. (2005) The mammalian unfolded protein response. *Annu. Rev. Biochem.* **74**, 739–789.
- (5) Rutkowski, D. T., and Kaufman, R. J. (2004) A trip to the ER: Coping with stress. *Trends Cell Biol.* **14**, 20–28.
- (6) Tabas, I., and Ron, D. (2011) Integrating the mechanisms of apoptosis induced by endoplasmic reticulum stress. *Nat. Cell Biol.* **13**, 184–190.
- (7) Walter, P., and Ron, D. (2011) The unfolded protein response: From stress pathway to homeostatic regulation. *Science* **334**, 1081–1086.
- (8) Zhang, K., Shen, X., Wu, J., Sakaki, K., Saunders, T., Rutkowski, D. T., Back, S. H., and Kaufman, R. J. (2006) Endoplasmic reticulum stress activates cleavage of CREBH to induce a systemic inflammatory response. *Cell* **124**, 587–599.
- (9) Bailey, D., and O'Hare, P. (2007) Transmembrane bZIP transcription factors in ER stress signaling and the unfolded protein response. *Antioxid. Redox Signaling* **9**, 2305–2321.
- (10) Boyce, M., Bryant, K. F., Jousse, C., Long, K., Harding, H. P., Scheuner, D., Kaufman, R. J., Ma, D., Coen, D. M., Ron, D., and Yuan, J. (2005) A selective inhibitor of eIF2alpha dephosphorylation protects cells from ER stress. *Science* **307**, 935–939.
- (11) Kim, I., Shu, C. W., Xu, W., Shiao, C. W., Grant, D., Vasile, S., Cosford, N. D., and Reed, J. C. (2009) Chemical biology investigation of cell death pathways activated by endoplasmic reticulum stress reveals cytoprotective modulators of ASK1. *J. Biol. Chem.* **284**, 1593–1603.
- (12) Cnop, M., Ladriere, L., Hekerman, P., Ortis, F., Cardozo, A. K., Dogusan, Z., Flamez, D., Boyce, M., Yuan, J., and Eizirik, D. L. (2007) Selective inhibition of eukaryotic translation initiation factor 2 alpha dephosphorylation potentiates fatty acid-induced endoplasmic reticulum stress and causes pancreatic beta-cell dysfunction and apoptosis. *J. Biol. Chem.* **282**, 3989–3997.
- (13) Ladriere, L., Igollo-Esteve, M., Cunha, D. A., Brion, J. P., Bugiani, M., Marchetti, P., Eizirik, D. L., and Cnop, M. (2010) Enhanced signaling downstream of ribonucleic Acid-activated protein kinase-like endoplasmic reticulum kinase potentiates lipotoxic endoplasmic reticulum stress in human islets. *J. Clin. Endocrinol. Metab.* **95**, 1442–1449.
- (14) Van Lommel, L., Janssens, K., Quintens, R., Tsukamoto, K., Vander Mierde, D., Lemaire, K., Denef, C., Jonas, J. C., Martens, G., Pipeleers, D., and Schuit, F. C. (2006) Probe-independent and direct quantification of insulin mRNA and growth hormone mRNA in enriched cell preparations. *Diabetes* **55**, 3214–3220.
- (15) Schuit, F. C., In't Veld, P. A., and Pipeleers, D. G. (1988) Glucose stimulates proinsulin biosynthesis by a dose-dependent recruitment of pancreatic beta cells. *Proc. Natl. Acad. Sci. U. S. A.* **85**, 3865–3869.
- (16) Samali, A., Fitzgerald, U., Deegan, S., and Gupta, S. (2010) Methods for monitoring endoplasmic reticulum stress and the unfolded protein response. *Int. J. Cell Biol.* **2010**, No. 830307.
- (17) Back, S. H., and Kaufman, R. J. (2012) Endoplasmic reticulum stress and type 2 diabetes. *Annu. Rev. Biochem.* **81**, 767–793.
- (18) Qiu, Y., Mao, T., Zhang, Y., Shao, M., You, J., Ding, Q., Chen, Y., Wu, D., Xie, D., Lin, X., Gao, X., Kaufman, R. J., Li, W., and Liu, Y. (2010) A crucial role for RACK1 in the regulation of glucose-stimulated IRE1alpha activation in pancreatic beta cells. *Sci. Signaling* **3**, ra7.
- (19) Eizirik, D. L., and Cnop, M. (2010) ER stress in pancreatic beta cells: The thin red line between adaptation and failure. *Sci. Signaling* **3**, pe7.
- (20) Osłowski, C. M., and Urano, F. (2011) The binary switch that controls the life and death decisions of ER stressed beta cells. *Curr. Opin. Cell Biol.* **23**, 207–215.
- (21) Han, D., Lerner, A. G., Vande Walle, L., Upton, J. P., Xu, W., Hagen, A., Backes, B. J., Oakes, S. A., and Papa, F. R. (2009) IRE1alpha kinase activation modes control alternate endoribonuclease outputs to determine divergent cell fates. *Cell* **138**, 562–575.
- (22) Lipson, K. L., Fonseca, S. G., Ishigaki, S., Nguyen, L. X., Foss, E., Bortell, R., Rossini, A. A., and Urano, F. (2006) Regulation of insulin biosynthesis in pancreatic beta cells by an endoplasmic reticulum-resident protein kinase IRE1. *Cell Metab.* **4**, 245–254.
- (23) Tabas, I., and Ron, D. (2011) Integrating the mechanisms of apoptosis induced by endoplasmic reticulum stress. *Nat. Cell Biol.* **13**, 184–190.
- (24) Ma, Y., Brewer, J. W., Diehl, J. A., and Hendershot, L. M. (2002) Two distinct stress signaling pathways converge upon the CHOP promoter during the mammalian unfolded protein response. *J. Mol. Biol.* **318**, 1351–1365.
- (25) Lipson, K. L., Ghosh, R., and Urano, F. (2008) The role of IRE1alpha in the degradation of insulin mRNA in pancreatic beta-cells. *PLoS One* **3**, No. e1648.
- (26) Novoa, I., Zeng, H., Harding, H. P., and Ron, D. (2001) Feedback inhibition of the unfolded protein response by GADD34-mediated dephosphorylation of eIF2alpha. *J. Cell Biol.* **153**, 1011–1022.
- (27) Shore, G. C., Papa, F. R., and Oakes, S. A. (2011) Signaling cell death from the endoplasmic reticulum stress response. *Curr. Opin. Cell Biol.* **23**, 143–149.
- (28) Hetz, C. (2012) The unfolded protein response: Controlling cell fate decisions under ER stress and beyond. *Nat. Rev. Mol. Cell Biol.* **13**, 89–102.
- (29) Weisberger, A. S. (1967) Inhibition of protein synthesis by chloramphenicol. *Annu. Rev. Med.* **18**, 483–494.
- (30) Han, J., Back, S. H., Hur, J., Lin, Y. H., Gildersleeve, R., Shan, J., Yuan, C. L., Krokowski, D., Wang, S., Hatzoglou, M., Kilberg, M. S., Sartor, M. A., and Kaufman, R. J. (2013) ER-stress-induced transcriptional regulation increases protein synthesis leading to cell death. *Nat. Cell Biol.* **15**, 481–490.
- (31) Krokowski, D., Han, J., Saikia, M., Majumder, M., Yuan, C. L., Guan, B. J., Bevilacqua, E., Bussolati, O., Broer, S., Arvan, P., Tchorzewski, M., Snider, M. D., Puchowicz, M., Croniger, C. M., Kimball, S. R., Pan, T., Koromilas, A. E., Kaufman, R. J., and Hatzoglou,

- M. (2013) A self-defeating anabolic program leads to beta-cell apoptosis in endoplasmic reticulum stress-induced diabetes via regulation of amino acid flux. *J. Biol. Chem.* 288, 17202–17213.
- (32) Guan, B. J., Krokowski, D., Majumder, M., Schmotzer, C. L., Kimball, S. R., Merrick, W. C., Koromilas, A. E., and Hatzoglou, M. (2014) Translational control during endoplasmic reticulum stress beyond phosphorylation of the translation initiation factor eIF2alpha. *J. Biol. Chem.* 289, 12593–12611.
- (33) Blais, J. D., Chin, K. T., Zito, E., Zhang, Y., Heldman, N., Harding, H. P., Fass, D., Thorpe, C., and Ron, D. (2010) A small molecule inhibitor of endoplasmic reticulum oxidation 1 (ERO1) with selectively reversible thiol reactivity. *J. Biol. Chem.* 285, 20993–21003.
- (34) Mimura, N., Fulciniti, M., Gorgun, G., Tai, Y. T., Cirstea, D., Santo, L., Hu, Y., Fabre, C., Minami, J., Ohguchi, H., Kiziltepe, T., Ikeda, H., Kawano, Y., French, M., Blumenthal, M., Tam, V., Kertesz, N. L., Malyankar, U. M., Hokenson, M., Pham, T., Zeng, Q., Patterson, J. B., Richardson, P. G., Munshi, N. C., and Anderson, K. C. (2012) Blockade of XBP1 splicing by inhibition of IRE1alpha is a promising therapeutic option in multiple myeloma. *Blood* 119, 5772–5781.
- (35) Papandreou, I., Denko, N. C., Olson, M., Van Melckebeke, H., Lust, S., Tam, A., Solow-Cordero, D. E., Bouley, D. M., Offner, F., Niwa, M., and Koong, A. C. (2011) Identification of an Ire1alpha endonuclease specific inhibitor with cytotoxic activity against human multiple myeloma. *Blood* 117, 1311–1314.
- (36) Wiseman, R. L., Zhang, Y., Lee, K. P., Harding, H. P., Haynes, C. M., Price, J., Sicheri, F., and Ron, D. (2010) Flavonol activation defines an unanticipated ligand-binding site in the kinase-RNase domain of IRE1. *Mol. Cell* 38, 291–304.
- (37) Wang, L., Perera, B. G., Hari, S. B., Bhattacharai, B., Backes, B. J., Seeliger, M. A., Schurer, S. C., Oakes, S. A., Papa, F. R., and Maly, D. J. (2012) Divergent allosteric control of the IRE1alpha endoribonuclease using kinase inhibitors. *Nat. Chem. Biol.* 8, 982–989.
- (38) Cross, B. C., Bond, P. J., Sadowski, P. G., Jha, B. K., Zak, J., Goodman, J. M., Silverman, R. H., Neubert, T. A., Baxendale, I. R., Ron, D., and Harding, H. P. (2012) The molecular basis for selective inhibition of unconventional mRNA splicing by an IRE1-binding small molecule. *Proc. Natl. Acad. Sci. U. S. A.* 109, E869–E878.
- (39) Volkmann, K., Lucas, J. L., Vuga, D., Wang, X., Brumm, D., Stiles, C., Kriebel, D., Der-Sarkissian, A., Krishnan, K., Schweitzer, C., Liu, Z., Malyankar, U. M., Chiovitti, D., Cann, M., Durocher, D., Sicheri, F., and Patterson, J. B. (2011) Potent and selective inhibitors of the inositol-requiring enzyme 1 endoribonuclease. *J. Biol. Chem.* 286, 12743–12755.
- (40) Desbordes, S. C., Placantonakis, D. G., Ciro, A., Socci, N. D., Lee, G., Djaballah, H., and Studer, L. (2008) High-throughput screening assay for the identification of compounds regulating self-renewal and differentiation in human embryonic stem cells. *Cell Stem Cell* 2, 602–612.
- (41) Lobel, L. I., Morseman, J. P., Zeng, X., Lustbader, J. W., Chen, H., and Allnutt, F. C. (2001) Development of a fluorescence based high throughput assay for antagonists of the human chorionic gonadotropin receptor extracellular domain: Analysis of peptide inhibitors. *J. Biomol. Screening* 6, 151–158.
- (42) Zhang, J. H., Chung, T. D., and Oldenburg, K. R. (1999) A Simple Statistical Parameter for Use in Evaluation and Validation of High Throughput Screening Assays. *J. Biomol. Screening* 4, 67–73.
- (43) Mayer, C. M., and Belsham, D. D. (2010) Palmitate attenuates insulin signaling and induces endoplasmic reticulum stress and apoptosis in hypothalamic neurons: rescue of resistance and apoptosis through adenosine 5' monophosphate-activated protein kinase activation. *Endocrinology* 151, 576–585.
- (44) Schmidt, E. K., Clavarino, G., Ceppi, M., and Pierre, P. (2009) SUNSET, a nonradioactive method to monitor protein synthesis. *Nat. Methods* 6, 275–277.