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Hes1 Inhibitor Isolated by Target Protein Oriented Natural Products Isolation (TPO-NAPI) of Differentiation Activators of Neural Stem Cells

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The Hes1 dimer inhibitor, agalloside (2), which can accelerate the differentiation of neural stem cells is described. Six natural products, including one new natural product, which bind to Hes1 were rapidly isolated by a developed “target protein oriented natural products isolation” (TPO-NAPI) method using Hes1-immobilized beads. Of the six compounds, 2 inhibited Hes1 dimer formation at both the protein- and cellular level. Neural stem cells treated with 2 differentiated to neurons with longer neurites than cells treated with varproic acid or retinoic acid. Moreover, 2 exhibited specificity for neurons. This promotion of differentiation was supported by an increase in the mRNA expression of the proneural genes, Mash1 and Ngn2, which were inhibited by Hes1.

Introduction

Neural stem cells (NSCs) can differentiate into neural cells such as neurons, astrocytes and oligodendrocytes. NSCs have been discovered in the adult mouse brain1 and the adult human brain (dentate gyrus,2 subventricular zone3). Endogenous or transplanted NSCs result in neurogenesis in response to injury.4-6 This discovery has lead to considerable research into identifying clinical methods for using NSCs to regenerate neuronal cells damaged by stroke, spinal cord injury, or neurodegenerative disorders. Small molecules that can accelerate the differentiation of NSCs were thus be regenerative drug candidates. Varproic acid has been reported to improve the restoration of hind leg function of spinal cord injury model mice.7 However, although there have been many reports of neurite-growth-promoting small molecules,8-12 the number of small molecules reported to accelerate the differentiation of neural stem cells is still quite limited.13-22

Basic-helix-loop-helix (bHLH) transcription factors control the fate of neural stem cells, i.e., their proliferation and differentiation.23-26 Activator-type bHLH factors such as Mash1 (also known as Ascl1), Neurogenin2 (Ngn2) and NeuroD affect the differentiation of NSCs to neural cells. On the other hand, repressor-type bHLH factors, such hairy and Enhancer of split 1 (Hes1) and Hes5, maintain NSCs in the undifferentiated form and enhance their self-proliferation. Hes1 inhibits the expression of activator-type bHLH factors by binding to the promoter region as a homo dimer to recruit the co-repressor, TLE/Grg. We postulated that small molecule inhibitors of Hes1 dimer formation would accelerate NSC differentiation.

Recent technical innovations in small molecule screening using huge small molecule libraries have lead to the successful use of reverse chemical genetics using immobilized target proteins.27-30 However, in contrast to the rapid innovations in large-scale screening, innovations in “target protein oriented natural product isolation” (TPO-NAPI) have developed more slowly.31-39 We previously reported an isolation of new natural products which bind a target protein using protein-immobilized beads-HPLC method.39 The ability of a natural product to bind to a target protein is important for estimating the bioactivity of the natural product. Thus, a target protein-beads-HPLC method would be a powerful approach for isolating bioactive natural compounds from natural product extracts.

Here we report target protein oriented natural products isolation (TPO-NAPI) using a protein-immobilized beads-HPLC method for NSCs differentiation activators. Six natural products, including one new compound, were isolated. One of these compounds, agalloside (2) accelerated NSC differentiation by disrupting dimer formation of Hes1, a repressor-type bHLH transcriptional factor. To the best of our knowledge, this is the first example of the acceleration of NSC differentiation by a Hes1 dimer inhibitor.
Results and Discussion

TPO-NAPI for Naturally Occurring Hes1 Inhibitors.

A schematic of an approach for Hes1-binding natural products is shown in Fig. 1. Glutathione-S-transferase (GST) fused Hes1-immobilized beads (GST-Hes1-beads) were mixed with our library of natural product extracts. The extracts provided many HPLC peaks, corresponding to the various natural product components (Fig. 1a). After incubation of the protein beads with an extract, the beads were washed to remove unbound natural products. Natural product components bound to Hes1 can be released by EtOH and heating, then analyzed by HPLC (Fig. 1d). The retention times and UV absorption patterns allow the desired natural product component to be followed easily during the fractionation and isolation steps. To help choose the most promising component, compounds which bind non-specifically were identified using beads with GST immobilized at the comparable concentration as GST-Hes1 (GST-Hes1: ca. 3.6 nmol/bed volume 100 µl beads, GST; ca. 3.8 nmol/bed volume 100 µl beads). Although there have been no reports of small molecules binding to Hes1, we previously identified Hes1 dimer inhibitors from our natural product library using the Hes1 dimer plate assay. Of these inhibitors, the natural product lindbladione (1) inhibits Hes1 dimer suppression of DNA expression in cells. Optimization of incubation time, buffer, detergent and the method for releasing the bound compound from the Sepharose beads lead to the Hes1-beads-HPLC method (see data in Supporting Information).

Using the Hes1-beads assay method, 177 extracts of tropical plants and 320 extracts of actinomycete strains were screened. The results from *Aquilaria agallocha* (leaves) collected in Thailand are shown in Fig. 2; other HPLC results of hit extracts are provided in Supporting Information. The left-hand HPLC profile shows the MeOH extract of *A. agallocha*; many UV-absorbing peaks are evident. After mixing with GST-Hes1 beads, followed by washing and release of the bound compounds by addition of EtOH and heating, the supernatant provided several peaks. Comparison of the HPLC results with those from GST-beads (control) lead to the isolation and identification of 7,4’-di-O-methylapigenin 5-O-β-D-xylosyl-β-D-glucoside (2), genkwanin 5-O-β-D-xylosyl-β-D-glucoside (3), and lethedioside A (4) as Hes1 binders (Fig. 3a). α-Mangostin (5) from *Garcinia mangostana* (calyx) collected in Thailand was rapidly isolated by just one HPLC separation step. A macrolactam, BE-14106 (6), was isolated from an AcOEt extract of *Actinoalloteichus cyanogriseus* IFM11549 from a soil sample collected at the Sakazuki forest in Chiba, Japan. A new natural product, a hydroxypiperidine with three conjugated double bonds, was named Inohanamine (7) and was also isolated using the HPLC peak guide approach. Compound 7 was isolated from an AcOEt extract of *Streptomyces sp.* IFM 11584 collected at Inohana Park in Chiba, Japan. The structure of 7 was determined by 1H and 13C-NMR, HRMS, HMBC, COSY, and NOE (Fig. 3b, and Supporting Information). The ability of the isolated compounds (2-7) to bind to Hes1 was verified using GST-Hes1 beads (see Supporting Information).

![Fig. 1 Schematic showing target protein-oriented natural product isolation by the Hes1 beads-HPLC method. a) HPLC profile of a natural product extract; b) incubation of the extract with Hes1 beads; c) washing the beads and release of compounds from Hes1; d) detection of the Hes1 binding natural product; e) representation of the Hes1 glutathione Sepharose beads.](image-url)
Inhibition using the TCF4/β-catenin complex inhibition, whereas 4 showed weak inhibition (Fig. 4f). This result indicated that Hes1 dimer inhibition by 2 is not due to nonspecific binding to the protein complex. Having confirmed Hes1 dimer inhibition by compound 2 (named agalloside; Aquilaria agallocha), 2 was investigated further. The electrostatic charge distributions of compounds with similar structure (2-4) were examined using DFT calculations (see Supporting Information). Only agalloside (2) has an obvious electron deficient area which might be one of the reasons its activity against Hes1.

To examine Hes1 dimer inhibition in cells, HA- and Flag-tagged Hes1 expression vectors (pCI-HA-Hes1, pCI-FLAG-Hes1) were prepared and transfected into C3H10T1/2 cells (Fig. 5), according to a reported method which can detect protein homo-dimers.30 Immunoprecipitation (IP) assays were performed using HA antibody beads. HA- and Flag-tagged Hes1 were detected by each antibody. Treating the cells with agalloside (2) (5 μM and 10 μM) clearly decreased Flag-Hes1 dose dependently, indicating that 2 inhibits Hes1 dimer formation in cells.

With these isolated Hes1-binding natural compounds in-hand, their ability to inhibit Hes1 dimer formation was examined using the Hes1 dimer plate assay.30 In this technique, Hes1 is immobilized on the bottom of a microplate and Cy3-labeled Hes1 is added (Fig. 4a). Hes1 dimer formation can be detected by measuring fluorescence intensity. Of the isolated Hes1 binding natural compounds, compounds 2 and 4 showed the highest Hes1 dimer inhibition: an IC50 of 10.1 μM and 9.5 μM, respectively (Fig. 4b). The flavones (8, 9), which are the core flavanone structures of 2 and 4, respectively (Fig. 4c), did not show Hes1 dimer inhibition, indicating that the entire structure, including the sugar, is needed for activity (Fig. 4d). Nonspecific inhibition was measured using a transcription factor, TCF (T-cell factor), and β-catenin complex, which is a key player in the transcription of Wnt signal-related target genes. An ELISA (enzyme-linked immunosorbent assay) for TCF4/β-catenin complex was constructed using a slight modification of a reported method (Fig. 4e).30 The reliability of the assay was confirmed using a known TCF4/β-catenin complex inhibitor, calphostin C (PKF115-584)30 (see Supporting Information). Compound 2 did not show TCF/β-catenin complex inhibition, whereas 4 showed weak inhibition (Fig. 4f). Next, the ability of 2 to accelerate NSCs was evaluated (Fig. 6). Multipotent mouse neural stem cells (MEBS)31 were treated with DMSO (control), valproic acid (100 μM), retinoic acid (20 μM) (positive controls) or agalloside (2) (5 μM and 10 μM) for four days. A confocal microscope was used to obtain images of differentiated neural cells after immunostaining class III β-tubulin (Tuj1) in neurons, and glial fibrillary acidic protein (GFAP) in astrocytes and nuclei (TO-PRO-3). The number of neurons and the length of the neurites were calculated for over 3000 cells and 800 neurites in each sample. Agalloside (2) exhibits potent neurite outgrowth promoting activity (Fig. 6b). The median value of neurite length (red bar) increased at a lower concentration of 2 compared to the concentration.
required for comparable increases by the positive controls (valproic acid and retinoic acid). Comparison of the number of neurons and astrocytes vs. the total number of cells showed increased neuronal differentiation with agalloside (2) (Fig. 6c). The differentiated neurons with 2 were 36.5 % (5 µM) and 39.3 % (10 µM), which are 36.2 % and 46.6 % increase compared to those of control. The differentiated astrocytes with 2 were 28.0 % (5 µM) and 33.5 % (10 µM), which are 0.0 % and 19.6 % increase compared to those of control. Agalloside (2) showed neuron specificity in differentiation.

Fig. 6 NSC differentiation-promoting activity. a) MEB5 cells were treated with DMSO (negative control), agalloside (2) (5 and 10 µM), VPA (positive control; 100 µM) or RA (positive control; 20 µM) for four days. The cells were then immunostained with Tuj1 (green) for neurons, GFAP (red) for astrocytes, and TO-PRO-3 (blue) for nuclei. Scale bar: 50 µm. DMSO = dimethylsulfoxide, VPA = valproic acid, RA = retinoic acid. VPA and RA were positive controls. b) Effects on the length of neurites. The lengths of the neurites are shown as box plots; middle bars (red) show the median values, each box and bar shows 25% of total number of neurites. Over 1200 neurites in each sample were measured. c) Effects on the number of neurons and astrocytes. Over 3000 cells in each sample were counted.

To elucidate the effect of 2 on mRNA expression of pro-neural genes (activator-type bHLH factors), the expression levels of Mash1, Ngn2 and NeuroD2 were examined (Fig. 7). It was previously reported that Mash1 represses expression by directly binding to the Mash1 promoter.32-34 Real-time RT-PCR showed that agalloside (2) up-regulates Mash1 after 24 h (Fig. 7a). Moreover, agalloside (2) cancelled the N-box dependent repression activity of Hes1 dimers35 in a dose-dependent manner (see Supporting Information). Taken together, it appears that agalloside (2) disrupts Hes1 dimer formation in NSCs, leading to upregulation of Mash1. This is the first report of the upregulation of a pro-neural gene by a Hes1 dimer inhibitor. Although it remains unknown whether the Hes1 dimer regulates directly or indirectly, Hes1 also regulates the expression of Ngn2.36 Sustained upregulation of Ngn2 is required for neural differentiation. Increased Ngn2 expression was clearly detected after treatment with 2 for 24 h (Fig. 7b), suggesting that agalloside (2) might inhibit the suppression of Ngn2 expression by Hes1. Moreover, the neuronal specificity of 2 for the differentiation of NSCs is supported by reports that Mash1 and Ngn2 suppress astrocytic gene expression.34-37 NeuroD2 is a late response activator-type bHLH factor, and Mash1 acts upstream of NeuroD2.26, 58 Cells treated with 2 expressed NeuroD2 more highly than the control after 48 h (Fig. 7c). The disruption of Hes1 dimer formation by 2 would increase the transcription of pro-neural genes such as Mash1 (Ascl1) and Ngn2, which activate the transcription of neurogenesis genes such as NeuroD2 (Fig. 7d).

The binding region of agalloside (2) in Hes1.

To predict the binding region of agalloside (2) in Hes1, partial proteins of Hes1 were synthesized (Fig. 8A). Agalloside (2) was mixed and incubated with each protein immobilized beads (Full, 1-95aa, 104-281aa, 47-281aa, 47-156aa, 151-281aa and GST only). After washing the beads, binding compound (2) was released by addition EtOH. Using HPLC, the binding amounts were compared as their UV absorption (Fig. 8B). The beads with Full Hes1, Part. A (1-95aa), Part. C (47-281aa), Part. D (47-156aa) showed significant agalloside (2) binding. These partial Hes1 proteins have HLH domain. On the other hand, the amount of agalloside (2) decreased after mixing with the beads of Part. B (104-281aa) and Part. E (151-281aa), which don’t have HLH domain. Fig. 8C shows predicted binding ability from the results of beads assay. These results indicated that agalloside (2) binding region in Hes1 can be predicted as HLH domain. We also predicted the interaction between HLH domain and agalloside (2) by performing in silico docking analysis. The sugar region of agalloside (2) might interact and disrupt the hydrophilic interaction between Arg46, Glu76 and Lys77, which would be important to make
proteins. In principle, the binding activity of ligands to proteins is expected to be useful for isolating natural products which bind to target proteins, and this strategy using TPO-NAPI to identify target compounds gives compounds the chance for a desired bioactivity. We thus report here the first example of a naturally occurring Hes1 dimer inhibitor, agalloside (2), which was isolated by the TPO-NAPI method using Hes1 immobilized beads. We demonstrated the isolation of six natural products, including one new compound, by TPOqNAPI. This method is useful for isolating natural products which bind to target proteins. In principle, the binding activity of ligands to proteins gives compounds the chance for a desired bioactivity. We thus believe that this strategy using TPOqNAPI to identify modulators bHLH factors will provide good candidates for development as regenerative drugs.

Conclusions

In conclusion, we report here the first example of a naturally occurring Hes1 dimer inhibitor, agalloside (2), which was isolated by the TPO-NAPI method using Hes1 immobilized beads. We demonstrated the isolation of six natural products, including one new compound, by TPO-NAPI. This method is useful for isolating natural products which bind to target proteins. In principle, the binding activity of ligands to proteins gives compounds the chance for a desired bioactivity. We thus believe that this strategy using TPO-NAPI to identify modulators bHLH factors will provide good candidates for development as regenerative drugs.

Experimental details

A typical screening procedure

To prepare GST-Hes1 beads, GST-Hes1 (200 µg, ca. 3.6 nmol) in PBS was added to pre-washed glutathione sepharose 4B beads (bed volume 100 µL, GE Healthcare) and they were mixed at 4 °C for 1 h. The GST-Hes1 beads were washed five times by NET buffer (20 mM Tris-HCl, pH 7.5, 200 mM NaCl, 1 mM EDTA), then the beads were suspended in NET buffer (250 µL). A MeOH or EtOAc extract of natural resources (125 µg in EtOH, 25 µL) was added to above GST-Hes1 freshly prepared beads (bed volume 100 µL) and the mixture was gently mixed for 2 h at 4 °C. The beads were then washed by a rotated-mixer at 4 °C for 10 min three times with NET-N buffer (NET buffer containing 0.05% Nonidet P-40, 500 µL). 70% EtOH (150 µL) was then added to the washed beads and the suspension was heating at 100 °C for 3 min. The beads were gathered by centrifugation (2000 rpm, 4 °C, 1 min) and the supernatant was centrifuged at 15000 rpm for 15 min. The one-third of the supernatant was analyzed by HPLC. The control GST-beads were also prepared in the same procedure of GST-Hes1 beads. GST (100 µg, ca. 3.8 nmol) in PBS was added to pre-washed glutathione sepharose 4B beads (bed volume 100 µL, GE Healthcare). If there is the obvious difference in the peak intensity between the results of GST-Hes1-beads and GST-beads (control), such extracts were obtained as “hit” extracts which had the Hes1 binding natural products.

Fluorescence plate assay for inhibitors of Hes1 dimer formation

Nunc Immobilizer™ Amino 96 well plate, white (Nalge Nunc Int.) was used for immobilizing of Hes1. The wells were incubated with 100 µL of Hes1 (10 µg mL⁻¹ in PBS) for 2 h at 4 °C. After the removal of protein solution, to block remaining activated unit on the well, the wells were incubated for 2 h at 4 °C with 100 µL of 10 mM ethanolamine (in 100 mM Na2CO3 buffer, pH 9.6), then washed twice with 200 µL of PBST (PBS containing 0.05% Tween 20). The Hes1 bound microplate wells were incubated with 50 µL of Cy3-labeled-Hes1 in NET-N buffer (ca. 7 mg L⁻¹, dye/protein = 0.65) for 24 h at 4 °C. After removal of protein solution, each well was washed twice with 200 µL of PBST, then dried under reduced pressure 1 h in the dark. The fluorescence intensity was measured in a microplate reader (Fluoroskan Ascent, Thermo). The Cy3 dye was excited at 530 nm and emitted at 590 nm. Usually, the assays were carried out in three individual wells, and the mean value and SD were calculated.

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J. Name., 2013, 00, 1-3 | 5
Notes and references