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Supplementary Data

Degradation of HaloTag-fused nuclear proteins using bestatin-HaloTag ligand

hybrid molecules

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<u>1. Experimental procedures</u>

1.1. Organic synthesis

General.

Proton nuclear magnetic resonance spectra (¹H NMR) and carbon nuclear magnetic resonance spectra (¹³C NMR) were recorded on a JEOL JNM-ECA500 (500 MHz) spectrometer in the indicated solvent. Chemical shifts (δ) are reported in parts per million relative to the internal standard tetramethylsilane (¹H NMR) or the centerline of

the triplet at 77.0 ppm of CDCl₃ (¹³C NMR). ¹H and ¹³C NMR spectra of compounds **1a-d** are shown in Figures S4-S7. Electrospray ionization (ESI) and fast atom bombardment (FAB) mass spectra were recorded on a BRUKER micrOTOF II mass spectrometer and JEOL JMA-HX110 mass spectrometer, respectively. Routine thin layer chromatography (TLC) was performed on silica gel 60 F254 plates (Merck, Germany). Flash column chromatography was performed on Silica gel 60 (spherical, particle size 40–100 µm; Kanto Chemical, Japan)

(S)-2-((2S,3R)-3-tert-Butoxycarbonylamino-2-

hydroxy-4-phenylbutanamido)-*N*-(2-(2-(2-(6-chlorohexyloxy)ethoxy)ethoxy)ethyl)-4-methylpentanamide (6a)

To a mixture of **4a** (25.1 mg, 93.6 μ mol), **5** (38.2 mg, 93.6 μ mol), 1-hydroxybenzotriazole monohydrate (20.3 mg, 150 μ mol) and DIEA (50 μ L, 281 μ mol) in DMF (0.5 mL) was added EDC (27.4 mg, 143 μ mol) at 0 °C. The reaction mixture was stirred at room temperature for 24 h, diluted with AcOEt, washed with brine/water (1:1), and dried over MgSO₄. Filtration, evaporation of the solvent *in vacuo*, and purification of the residue by flash column chromatography (CHCl₃/MeOH = 100:1 to 30:1) gave 48.7 mg (79%) of compound **6a** as a colorless amorphous solid. ¹H NMR (500 MHz, CDCl₃) δ 7.32 – 7.19 (m, 5H), 6.79 (s, 1H), 5.59 (s, 1H), 5.09 (s, 1H), 4.48 (br s, 1H), 4.13 (d, J = 4.6 Hz, 1H), 3.64 – 3.44 (m, 16H), 3.02 (d, J = 28.6 Hz, 2H), 1.80 – 1.74 (m, 2H), 1.70 – 1.59 (m, 5H), 1.48 – 1.23 (m, 13H), 0.92 (dd, J = 14.6, 6.0 Hz, 6H). MS (ESI) m/z 680 (M + Na)⁺.

(S)-2-((2S,3R)-3-*tert*-Butoxycarbonylamino-2-hydroxy-4-phenylbutanamido)-*N*-(2-(2-(2-(6-chlorohexyloxy)ethoxy)ethoxy)ethoxy)ethyl)-4-methylpentanamide (6b)

The title compound was prepared from **4b** (21.9 mg, 70.2 μ mol) according to the procedure described for **6a**. Yield: 39.7 mg (81%). Colorless amorphous solid. ¹H NMR (500 MHz, CDCl₃) δ 7.31 – 7.20 (m, 5H), 6.89 (s, 1H), 5.61 (s, 1H), 5.12 (br s, 1H), 4.49 (br s, 1H), 4.13 (br s, 1H), 3.65 – 3.44 (m, 20H), 3.00 (br s, 2H), 1.79 – 1.74 (m, 2H), 1.70 – 1.56 (m, 5H), 1.47 – 1.26 (m, 13H), 0.92 (dd, *J* = 14.9, 6.3 Hz, 6H). MS (ESI) m/z 724 (M + Na)⁺.

(*S*)-2-((2*S*,3*R*)-3-*tert*-Butoxycarbonylamino-2-hydroxy-4-phenylbutanamido)-*N*-(2-(2-(2-(2-(2-(6-chlorohexyloxy)ethoxy)ethoxy)ethoxy)ethoxy)ethyl)-4-methylpentana mide (6c)

The title compound was prepared from 4c (11.8 mg, 33.3 µmol) according to the

procedure described for **6a**. Yield: 18.7 mg (75%). Colorless amorphous solid. ¹H NMR (500 MHz, CDCl₃) δ 7.27 – 7.17 (m, 5H), 4.47 (dd, *J* = 9.5, 5.4 Hz, 1H), 4.15 (dd, *J* = 7.7, 5.4 Hz, 1H), 3.97 (s, 1H), 3.65 – 3.51 (m, 20H), 3.47 (t, *J* = 6.6 Hz, 2H), 3.37 – 3.34 (m, 2H), 2.88 – 2.84 (m, 2H), 1.79 – 1.73 (m, 2H), 1.67 – 1.55 (m, 5H), 1.45 – 1.37 (m, 13H), 0.93 (dd, *J* = 20.0, 6.3 Hz, 6H). MS (FAB) m/z: 747 (M + H)⁺.

(*S*)-2-((2*S*,3*R*)-3-*tert*-Butoxycarbonylamino-2-hydroxy-4-phenylbutanamido)-*N*-(2-(2-(2-(2-(2-(2-(6-chlorohexyloxy)ethoxy)ethoxy)ethoxy)ethoxy)ethoxy)ethyl)-4-meth ylpentanamide (6d)

The title compound was prepared from **4b** (13.7 mg, 34.2 µmol) according to the procedure described for **6a**. Yield: 20.9 mg (77%). Colorless amorphous solid. ¹H NMR (500 MHz, CDCl₃) δ 7.28 – 7.20 (m, 5H), 5.56 (d, *J* = 9.2 Hz, 1H), 4.46 (t, *J* = 7.4 Hz, 1H), 4.13 (d, *J* = 7.4 Hz, 1H), 4.02 (s, 1H), 3.67 – 3.53 (m, 24H), 3.48 (t, *J* = 6.9 Hz, 2H), 3.39 (d, *J* = 5.2 Hz, 2H), 2.94 – 2.84 (m, 2H), 1.81 – 1.75 (m, 2H), 1.64 – 1.59 (m, 5H), 1.50 – 1.44 (m, 2H), 1.41 – 1.35 (m, 11H), 0.94 (dd, *J* = 17.8 and 6.3 Hz, 6H). MS (ESI) m/z: 812 (M + Na)⁺.

(S)-2-((2S,3R)-3-Amino-2-hydroxy-4-phenylbutanamido)-N-(2-(2-(2-(6-chlorohexyl

oxy)ethoxy)ethoxy)ethyl)-4-methylpentanamide (1a)

4 M HCl/1,4-dioxane (1.0 mL) was added to a solution of **6a** (48.7 mg, 74.0 µmol) in DCM (1.0 mL) and the mixture was stirred at room temperature for 4 h. Evaporation of the solvent *in vacuo* and purification of the residue by flash column chromatography (CHCl₃/MeOH = 100:1 to 30:1) gave 41.0 mg (99%) of compound **1a** as a colorless amorphous solid. ¹H NMR (500 MHz, CD₃OD) δ 7.32 – 7.20 (m, 5H), 4.43 (dd, *J* = 8.9, 5.4 Hz, 1H), 3.93 (d, *J* = 2.9 Hz, 1H), 3.60 – 3.46 (m, 14H), 3.39 – 3.31 (m, 2H), 2.78 (dq, *J* = 118.4, 7.0 Hz, 2H), 1.79 – 1.73 (m, 2H), 1.68 – 1.56 (m, 5H), 1.48 – 1.37 (m, 4H), 0.95 (dd, *J* = 10.6 and 6.0 Hz, 6H). ¹³C NMR (125 MHz, a mixture of CDCl₃/CD₃OD) δ 173.37, 172.60, 137.97, 129.06, 128.43, 126.41, 77.58, 72.05, 71.07, 70.23, 69.83, 69.69, 69.29, 54.66, 51.27, 44.76, 40.84, 39.02, 32.26, 29.09, 26.41, 25.09, 24.60, 22.60, 21.39. HRMS (ESI) m/z: calcd for C₂₈H₄₉CIN₃O₆⁺, 558.3304; found 558.3321.

(*S*)-2-((2*S*,3*R*)-3-Amino-2-hydroxy-4-phenylbutanamido)-*N*-(2-(2-(2-(2-(2-(6-chlorohe xyloxy)ethoxy)ethoxy)ethoxy)ethyl)-4-methylpentanamide (1b)

The title compound was prepared from **6b** (39.7 mg, 56.5 μ mol) according to the procedure described for **1a**. Yield: 35.2 mg (100%). Colorless amorphous solid. ¹H

NMR (500 MHz, a mixture of CDCl₃/CD₃OD) δ 7.33 – 7.24 (m, 5H), 4.44 (s, 1H), 3.98 (s, 1H), 3.661 – 3.36 (m, 21H), 2.81 (dq, *J* = 134.6, 6.9 Hz, 2H), 1.78 (t, *J* = 7.4 Hz, 2H), 1.63 – 1.59 (m, 5H), 1.49 – 1.43 (m, 2H), 1.41 – 1.35 (m, 2H), 0.95 (dd, *J* = 10.0, 4.9 Hz, 6H). ¹³C NMR (125 MHz, a mixture of CDCl₃/CD₃OD) δ 173.44, 172.62, 138.10, 128.99, 128.35, 126.29, 72.21, 70.99, 70.19, 70.16, 70.12, 69.77, 69.68, 69.24, 54.61, 51.17, 44.68, 40.81, 39.10, 38.98, 32.22, 29.04, 26.35, 25.05, 24.55, 22.53, 21.30. HRMS (ESI) m/z: calcd for C₃₀H₅₃ClN₃O₇⁺, 602.3567; found 602.3554.

(S)-2-((2S,3R)-3-Amino-2-hydroxy-4-phenylbutanamido)-N-(2-(2-(2-(2-(2-(2-(6-chloro hexyloxy)ethoxy)ethoxy)ethoxy)ethoxy)ethoxy)ethoxy)ethyl)-4-methylpentanamide (1c)

The title compound was prepared from **6c** (7.8 mg, 10.5 μ mol) according to the procedure described for **1a**. Yield: 3.7 mg (54%). Colorless amorphous solid. ¹H NMR (500 MHz, a mixture of CDCl₃/CD₃OD) δ 7.34 – 7.22 (m, 5H), 4.46 (t, *J* = 7.2 Hz, 1H), 3.97 (d, *J* = 2.9 Hz, 1H), 3.68 – 3.54 (m, 20H), 3.50 (t, *J* = 6.6 Hz, 2H), 3.42 – 3.36 (m, 3H), 2.81 (dq, *J* = 121.6, 6.9 Hz, 2H), 1.82 – 1.76 (m, 2H), 1.69 – 1.59 (m, 5H), 1.52 – 1.46 (m, 2H), 1.44 – 1.339 (m, 2H), 0.98 (dd, *J* = 10.6 and 6.0 Hz, 6H). ¹³C NMR (125 MHz, CD₃OD) δ 174.88, 172.62, 139.10, 130.45, 129.80, 127.86, 72.17, 71.58, 71.55, 71.53, 71.24, 71.18, 70.46, 56.55, 53.15, 45.71, 42.11, 40.46, 40.41, 39.53, 33.77, 30.55,

27.73, 26.51, 26.03, 23.37, 22.22. HRMS (ESI) m/z: calcd for C₃₂H₅₇ClN₃O₈⁺, 646.3829; found 646.3850.

The title compound was prepared from **6b** (9.4 mg, 11.9 µmol) according to the procedure described for **1a**. Yield: 5.3 mg (65%). Colorless amorphous solid. ¹H NMR (500 MHz, a mixture of CDCl₃/CD₃OD) δ 7.33 – 7.21 (m, 5H), 4.45 (t, *J* = 7.2 Hz, 1H), 3.97 (d, *J* = 2.9 Hz, 1H), 3.71 – 3.53 (m, 24H), 3.49 (t, *J* = 6.6 Hz, 2H), 3.40 – 3.36 (m, 3H), 2.80 (dq, *J* = 125.9, 6.9 Hz, 2H), 1.81 – 1.75 (m, 2H), 1.65 – 1.58 (m, 5H), 1.49 – 1.44 (m, 2H), 1.42 – 1.37 (m, 2H), 0.96 (dd, *J* = 10.9 and 6.3 Hz, 6H). ¹³C NMR (125 MHz, CD₃OD) δ 175.18, 174.64, 139.62, 130.44, 129.72, 127.70, 73.11, 72.16, 71.56, 71.54, 71.25, 71.19, 70.48, 56.60, 53.07, 45.71, 42.14, 40.45, 40.42, 40.18, 33.77, 30.56, 27.74, 26.51, 26.04, 23.39, 22.20. HRMS (ESI) m/z: calcd for C₃₄H₆₁ClN₃O₉⁺, 690.4091; found 690.4090.

1.2. Biological assay

Cell culture condition and transfection.

Human embryonic kidney HEK293 cells were cultured in D-MEM containing 5% heat-inactivated fetal bovine serum (FBS), and penicillin and streptomycin mixture at 37 °C in a humidified atmosphere of 5% CO₂ in air. Breast cancer cell line MCF-7 cells were cultured in D-MEM containing 10% heat-inactivated FBS, and penicillin and streptomycin mixture at 37 °C in a humidified atmosphere of 5% CO₂ in air.

HEK293 cells stably expressing HaloTag-CREB1 were established by co-transfection with HaloTag 7-CREB1 cDNA (Kazusa DNA Res. Inst.) and mRFP cDNA (OriGene Technologies, Inc.: for selection) using Lipofectamine LTX reagent and PLUS reagent (Invitrogen), and G418 (Nacalai tesque) selection. MCF-7 cells were transiently transfected with HaloTag 7-c-jun cDNA (Kazusa DNA Res. Inst.) using Lipofectamine LTX reagent and PLUS reagent according to the manufacturer's instructions. Four hours after transfection, indicated compounds were treated for 21 h.

Western blotting.

Cells were washed with PBS, lysed in SDS lysis buffer (1% SDS, 10 mM EDTA and 50 mM Tris, pH 8.1) and boiled for 5 min. Protein concentrations were determined

using bicinchoninic acid (BCA) protein assay and normalized by total protein concentration in each lysate. After boiling for 5 min with Laemmli buffer, each lysate resolved by sodium dodecyl sulfate-polyacrylamide gel electrophoresis was (SDS-PAGE) with SuperSepTM Ace 10-20% (Wako Pure Chemical Industries) and transferred onto PVDF membrane. After blocking with TBS-T (20 mM Tris, 137 mM NaCl, 0.1% Tween 20, pH 7.5) containing 5% skim milk, the transblotted membrane was probed with anti-HaloTag rabbit polyclonal antibody (Promega, 1:1000), anti-lamin antibody (Santa Cruz Biotechnology, Inc., 1:500), anti-β-tubulin antibody (Boeringer Mannheim, 1:200), anti-\beta-actin antibody-horseradish peroxidase (HRP) conjugates (Santa Cruz Biotechnology, Inc., 1:1000), anti-mouse IgG-HRP conjugates (Millipore, 1:1000), and anti-rabbit IgG-HRP conjugates (Amerham, 1:2000) in Can-Get-Signal solution (Toyobo). After probing, the membrane was washed twice more with TBS-T. The immunoblots were visualized by enhanced chemiluminescence with ImmobilonTM Western Chemiluminescent HRP Substrate (Millipore).

Nuclear and cytoplasmic protein extraction

HEK293 cells were harvested with trypsin-EDTA and the cytoplasmic and nuclear fractions were extracted using NE-PER Nuclear and Cytoplasmic Extraction Reagent

kit (Thermo Scientific) according to the manufacturer's instructions.

Fluorescence microscopic analysis

HaloTag-fused proteins expressed in HEK293 cells or MCF-7 cells on glass-base dishes were labeled with HaloTag Oregon Green Ligand (Promega) according to the manufacturer's instructions, fixed with 10% formalin-PBS containing 0.4 µg/mL Hoechst 33342 (ICN Biomedicals) at room temperature for 30 min, and washed with PBS containing 0.05% Tween 20. Images were acquired using an IX70 inverted fluorescence microscope (Olympus).

WST-1 cell viability assay

Toxicity of compound **1b** was measured using Cell Counting Kit (Dojindo) according to the manufacturer's instructions.

2. Supplemental Figure



Figure S1. 6 h treatment of compound **1b** at 10 μ M reduced significantly HaloTag-CREB1 levels in HEK293 cells stably expressing HaloTag-CREB1. Signal intensities compared using an unpaired, two-sided Student's *t*-test. The *P*-value is indicated by an asterisk (**P*<0.05). Error bars represent standard errors. Each assay was carried out individually seven times.



Figure S2. Compound 1b showed low toxicity in HEK293 cells. WST-1 cell viability assay was performed after treatment for the indicated time with compound 1b at 10 μ M.

Signal intensities were compared using an unpaired, two-sided Student's *t*-test. The *P*-value is indicated by an asterisk (*P<0.05). n.s. stands for not significant. Error bars represent standard errors. Each assay was carried out once in triplicate.



Figure S3. HaloTag-c-jun localized in the nucleus was degraded upon addition of compound **1a** or **1b** to MCF-7 cells transiently expressing HaloTag-c-jun. (a) Fluorescence-microscopic analysis of cellular localization of HaloTag-c-jun in MCF-7 cells transiently expressing HaloTag-c-jun. Left picture: HaloTag-c-jun stained with HaloTag Oregon Green Ligand. Middle picture: cell nuclei stained with Hoechst. Right picture: merged image. (b) Western blot analysis was performed after treatment for 21 h with the indicated concentration of compound **1a** or **1b**.

3. NMR Spectra





Figure S4. ¹H and ¹³C NMR spectra of 1a.

Figure S5. ¹H and ¹³C NMR spectra of 1b.



Figure S6. ¹H and ¹³C NMR spectra of 1c.



Figure S7. ¹H and ¹³C NMR spectra of 1d.