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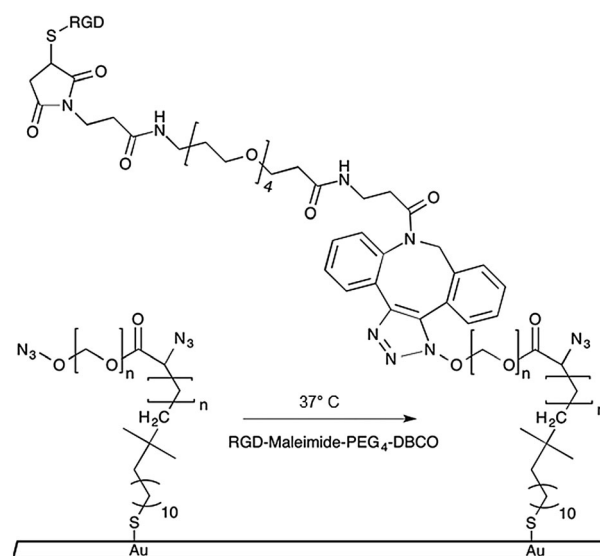
We describe a modular culture platform that enables spatiotemporal control of the morphology of 2D neural tissues derived from human pluripotent stem cells (hPSCs) by simply adding clickable peptides to the media. It should be widely applicable for elucidating how spatiotemporal changes in morphology and substrate biochemistry regulate tissue morphogenesis.

When differentiated as high density 2- and 3-D aggregates, human pluripotent stem cells (hPSCs), *i.e.* human embryonic and induced pluripotent stem cells, can spontaneously form tissues that recapitulate early stages of developmental morphogenesis. In 2-D culture, this was first observed during neural differentiation of hPSCs,¹ but the seemingly limitless potential of hPSCs in *in vitro* morphogenesis was only recently realized with the derivation of 3-D brain, retinal, intestinal, and kidney organoids.² Such tissues contain microscale structures with architectures mimetic of respective developing human tissues. However, orchestration of the morphogenesis process at the macroscale is chaotic, generating tissues with unnatural morphologies and anatomy.³ To fully harness the capabilities of hPSCs and advance towards reproducible engineering of organoids with biomimetic anatomy, culture platforms that enable facile, *in situ* spatiotemporal control of hPSC-derived tissue morphology and cellular differentiation must be developed.

Current methods for inducing *in situ* spatiotemporal changes in tissue morphology *in vitro* require perturbations of ideal culture conditions such as temperature,⁴ pH,⁵ UV light exposure,⁶ and solvent concentrations⁷ or physical destruction of parts of the tissue or culture substrate. Additionally, approaches using lasers⁸ or electrochemistry⁹ to actuate *in situ* reactions require complex integration of the culture system with specialized equipment

Micropatterned, clickable culture substrates enable *in situ* spatiotemporal control of human PSC-derived neural tissue morphology†

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Scheme 1 Azide-functionalized PEGMA-grafted substrates undergo 1,3-dipolar cycloaddition reaction with DBCO conjugated RGD-peptides.

thereby limiting their usage. To avoid such complications, we developed a culture platform in which coverslip substrates are engineered *a priori* with micropatterned PEG brushes presenting azide groups that can undergo copper-free click reactions with modular peptide-DBCO conjugates.^{10,11} Upon media supplementation, the peptide conjugates are readily immobilized onto the culture substrates in a spatiotemporal and quantitative manner (Scheme 1). Using clickable conjugates with biomimetic fibronectin peptide sequences, we demonstrated *in situ* conversion of inert PEG brushes, which initially confined hPSC-derived neural tissues to a microscale circular morphology, into biospecific, cell-adhesive substrates that permitted radial tissue growth. This progression in tissue morphology mimics early morphogenesis of the developing central nervous system (Fig. S1A, ESI⁺), and generated arrays of tissues with architecture analogous to developing neural tube slice cultures. Therefore, our methodology for actuating spatiotemporal changes in the morphology of 2-D hPSC-derived

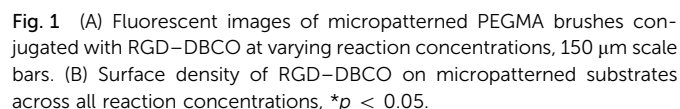
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To test our culture system's ability to actuate tissue morphology changes in an *in situ* spatiotemporal manner, micropatterned substrates were fabricated with PEGMA-azide brushes everywhere except for an array of 300 or 900 μm diameter circles (Fig. 2A). The substrates were coated with 0.083 mg mL^{-1} matrigel in E6 media overnight at 37°C and seeded with neural stem cells (NSCs) derived from WA09 hPSCs, as described and characterized in detail



The generation of truly biomimetic tissues by harnessing *in vitro* morphogenesis of hPSCs will only be possible using culture platforms that enable spatiotemporal control of tissue morphology and cellular differentiation. Here, we described a culture platform based on micropatterned, clickable culture substrates that permits facile alteration of substrate biochemistry in a

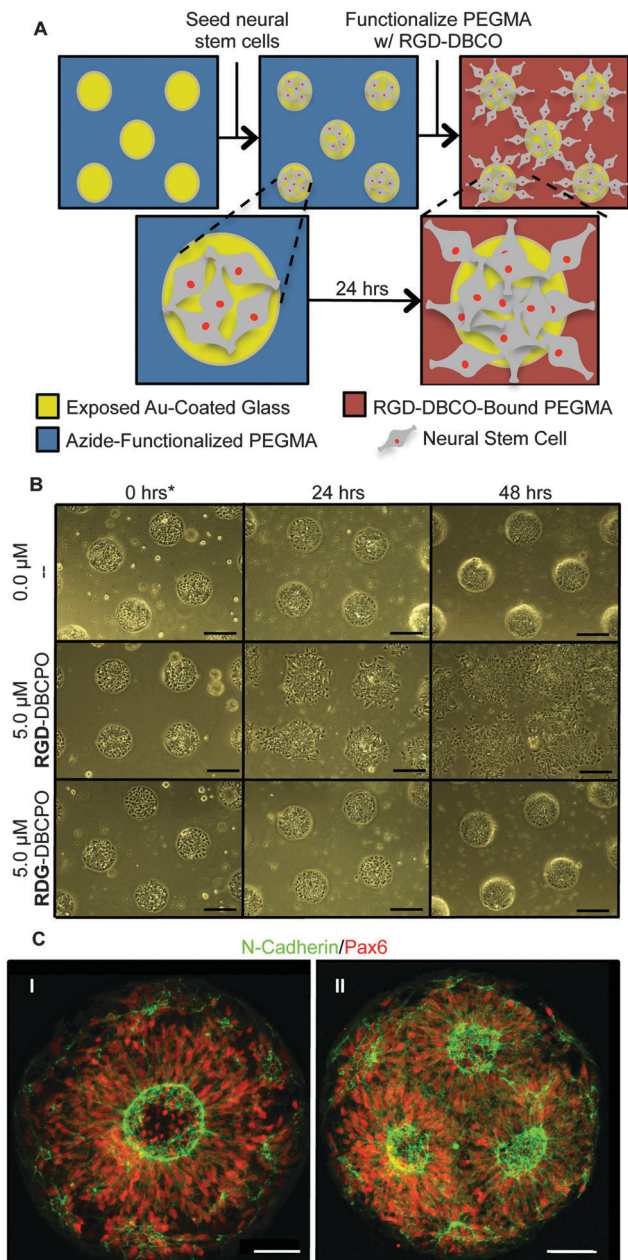


Fig. 2 (A) Schematic of neural tissue outgrowth onto RGD-DBCO-modified micropatterned substrates. (B) Bright field images of neural tissue outgrowth onto PEGMA brushes following addition of RGD-DBCO at time = 0, 300 μm scale bars. (C) Fluorescent images of polarized NSCs on micropatterned substrates, 50 μm scale bars.

chemically defined, *in situ*, and spatiotemporal manner to dynamically regulate the morphology of hPSC-derived neural tissues. Additionally, the culture substrates could be engineered with multicomponent PEG brushes using robotic microcontact printing,¹⁸ which could be used to not only actuate a change in tissue morphology, but also confine tissues to a second pre-determined morphology. Given the variety of bioorthogonal and biocompatible “click” chemistry motifs available,¹⁹ the substrates could also be engineered to present multiple biological ligands, each in a discrete, physiologically relevant, microscale spatial orientation.²⁰ Plus, the biospecific cell-ligand interactions enabled by

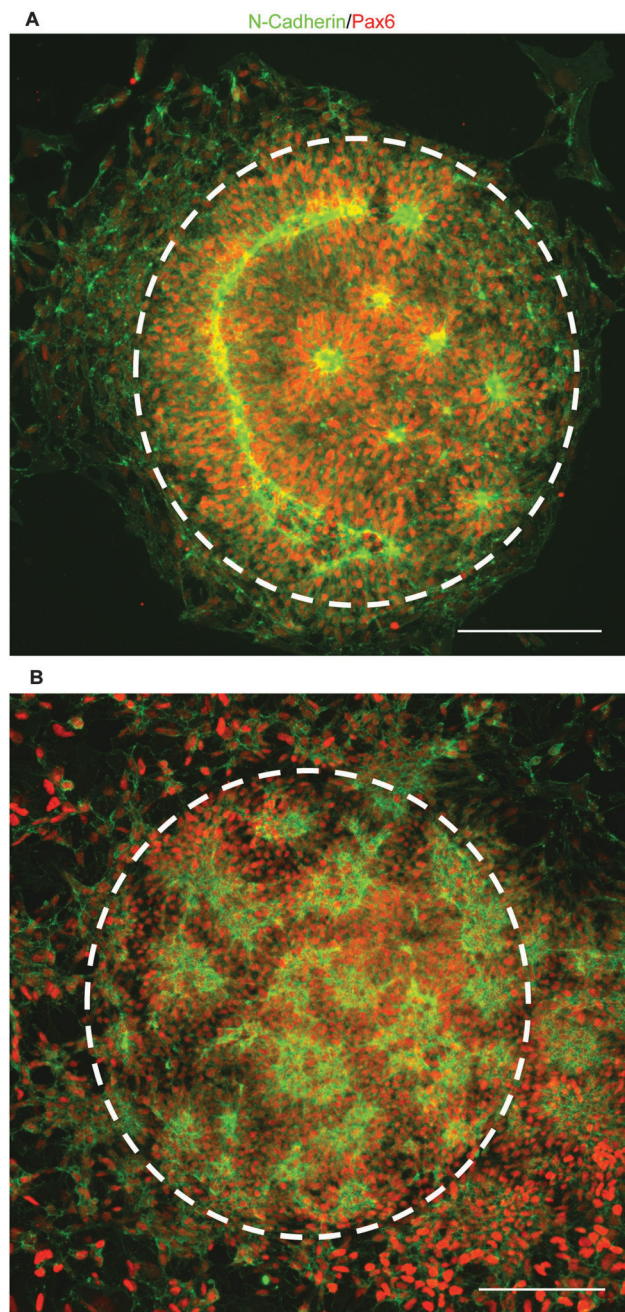


Fig. 3 (A) Fluorescent images of neural tissues with a polarized NSC core and radial expansion due to migrating progeny at 24 (B) and 96 h after supplementation with 10.0 μM RGD-DBCO, 250 μm scale bars.

peptide conjugated PEG brushes will facilitate reductionistic experimentation to elucidate the effects of pertinent biological cues on cell fate.^{10,21} Thus, micropatterned clickable substrates provide a highly modular culture platform for investigating how spatiotemporal changes in morphology and substrate biochemistry can be used to control *in vitro* morphogenesis of hPSC-derived tissue. Due to its compatibility with standard culture techniques, this approach should be broadly applicable in advancing our ability to generate hPSC-derived tissues *in vitro* with biomimetic anatomy.



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Notes and references

- 1 S. C. Zhang, M. Wernig, I. D. Duncan, O. Brüstle and J. A. Thomson, *In vitro* differentiation of transplantable neural precursors from human embryonic stem cells, *Nat. Biotechnol.*, 2001, **19**, 1129–1133.
- 2 M. A. Lancaster and J. A. Knoblich, Organogenesis in a dish: Modeling development and disease using organoid technologies, *Science*, 2014, **345**, 1247125.
- 3 M. A. Lancaster, *et al.* Cerebral organoids model human brain development and microcephaly, *Nature*, 2013, **501**, 373–379.
- 4 Y. Tsuda, *et al.* The use of patterned dual thermoresponsive surfaces for the collective recovery as co-cultured cell sheets, *Biomaterials*, 2005, **26**, 1885–1893.
- 5 J. Zhang, *et al.* Rapid pH/temperature-responsive cationic hydrogels with dual stimuli-sensitive grafted side chains, *Polymer*, 2009, **50**, 2516–2525.
- 6 S. B. Rahane, R. M. Hensarling, B. J. Sparks, C. M. Stafford and D. L. Patton, Synthesis of multifunctional polymer brush surfaces via sequential and orthogonal thiol-click reactions, *J. Mater. Chem.*, 2011, **22**, 932–943.
- 7 Y. Qiu and K. Park, Environment-sensitive hydrogels for drug delivery, *Adv. Drug Delivery Rev.*, 2001, **53**, 321–339.
- 8 C. A. DeForest, B. D. Polizzotti and K. S. Anseth, Sequential click reactions for synthesizing and patterning three-dimensional cell microenvironments, *Nat. Mater.*, 2009, **8**, 659–664.
- 9 S. Raghavan, R. A. Desai, Y. Kwon, M. Mrksich and C. S. Chen, Micropatterned Dynamically Adhesive Substrates for Cell Migration, *Langmuir*, 2010, **26**, 17733–17738.
- 10 J. Sha, E. S. Lippmann, J. McNulty, Y. Ma and R. S. Ashton, Sequential Nucleophilic Substitutions Permit Orthogonal Click Functionalization of Multicomponent PEG Brushes, *Biomacromolecules*, 2013, **14**, 3294–3303.
- 11 J. C. Jewett and C. R. Bertozzi, Cu-free click cycloaddition reactions in chemical biology, *Chem. Soc. Rev.*, 2010, **39**, 1272–1279.
- 12 M. Mrksich, L. E. Dike, J. Tien, D. E. Ingber and G. M. Whitesides, Using microcontact printing to pattern the attachment of mammalian cells to self-assembled monolayers of alkanethiolates on transparent films of gold and silver, *Exp. Cell Res.*, 1997, **235**, 305–313.
- 13 H. Ma, J. Hyun, P. Stiller and A. Chilkoti, 'Non-Fouling' Oligo-(ethylene glycol)-Functionalized Polymer Brushes Synthesized by Surface-Initiated Atom Transfer Radical Polymerization, *Adv. Mater.*, 2004, **16**, 338–341.
- 14 H. Gao and K. Matyjaszewski, Synthesis of Molecular Brushes by 'Grafting onto' Method: Combination of ATRP and Click Reactions, *J. Am. Chem. Soc.*, 2007, **129**, 6633–6639.
- 15 S. Tugulu, P. Silacci, N. Stergiopoulos and H.-A. Klok, RGD-Functionalized polymer brushes as substrates for the integrin specific adhesion of human umbilical vein endothelial cells, *Biomaterials*, 2007, **28**, 2536–2546.
- 16 E. S. Lippmann, M. C. Estevez-Silva and R. S. Ashton, Defined Human Pluripotent Stem Cell Culture Enables Highly Efficient Neuroepithelium Derivation Without Small Molecule Inhibitors, *Stem Cells*, 2014, **32**, 1032–1042.
- 17 Y. Shi, P. Kirwan, J. Smith, H. P. C. Robinson and F. J. Livesey, Human cerebral cortex development from pluripotent stem cells to functional excitatory synapses, *Nat. Neurosci.*, 2012, **15**, 477–486.
- 18 J. McNulty, *et al.* High-precision robotic microcontact printing (R-μCP) utilizing a vision guided selectively compliant articulated robotic arm, *Lab Chip*, 2014, **14**, 1923–1930.
- 19 C. R. Becer, R. Hoogenboom and U. S. Schubert, Click Chemistry beyond Metal-Catalyzed Cycloaddition, *Angew. Chem., Int. Ed.*, 2009, **48**, 4900–4908.
- 20 G. T. Knight, T. Klann, J. D. McNulty and R. S. Ashton, Fabricating Complex Culture Substrates Using Robotic Microcontact Printing (R-μCP) and Sequential Nucleophilic Substitution, *JoVE*, 2014, **92**, e52186.
- 21 R. S. Ashton, A. J. Keung, J. Peltier and D. V. Schaffer, Progress and Prospects for Stem Cell Engineering, *Annu. Rev. Chem. Biomol. Eng.*, 2011, **2**, 479–502.

