Screening of Hydrogels for Human Pluripotent Stem Cell–Derived Neural Cells: HyaluronanPolyvinyl AlcoholCollagenBased Interpenetrating Polymer Network Provides an Improved Hydrogel Scaffold

COVER PAGE

In this work we present a wide comparison of different 3D scaffolds for neuronal tissue engineering, especially when developing relevant in vitro models. As one of the main outcomes, this study gives us an interpenetrated network (IPN) hydrogel, which is supporting and enabling adhesion of the cells by its collagen I component. We were able to synthesize the IPN hydrogel by developing and utilizing a Principal Component Analysis (PCA) tool to analyze measured and indexed data comparing several human-based neural cell types and multiple hydrogel compositions. Comparison of neuronal cell and fibroblast adhesion to the surrounding environment revealed that integrin α6β4 is a neuronal cell-specific adhesion marker in both 2D and 3D cultures.

DOI: 10.1002/marc.((insert number)) ((or ppap., mabi., macp., mame., mren., mats.))

Full paper

Screening of hydrogels reveals that a hyaluronan-polyvinyl alcohol-collagen-based interpenetrating polymer network hydrogel provides an improved scaffold for human pluripotent stem cell-derived neural cells

Laura Ylä-Outinen*,†, Venla Harju†, Tiina Joki, Janne T. Koivisto, Jennika Karvinen, Minna Kellomäki, Susanna Narkilahti

_____

Dr. L. Ylä-Outinen, V. Harju, Dr. T. Joki, Dr. S. Narkilahti
NeuroGroup, Faculty of Medicine and Health Technology, Tampere University
Arvo Ylpön katu 34
33014 Tampere
Finland
E-mail: Laura.Yla-Outinen@tuni.fi

J.T. Koivisto, Dr. J. Karvinen, Prof. M. Kellomäki
Biomaterials & Tissue Engineering Group, Faculty of Medicine and Health Technology, Tampere University
Korkeakoulunkatu 6
33014 Tampere
Finland

† *equal contribution*

**corresponding author*

To better understand natural behavior of neuronal cells, it is beneficial to study them in in vivo mimicking conditions in vitro. Development of in vitro neural models is a multiparameter task consisting of cell-, biomaterial- and environment-related parameters and producing great amount of data. In this study three human pluripotent stem cell (hPSC) -derived neuronal cell types from different sources did not give similar results when cultured 3D in different hydrogel compositions. Additionally, studied cell adhesion of neurons differed greatly from that observed for fibroblasts. Importantly, integrin α6β4 seemed to be a neuron-specific adhesion molecule. Finding indicates that fibroblasts cannot be used to simulate neurons e.g. when optimizing biomaterial for in vitro models and care is also needed to select suitable hPSC cell source. To analyze measured and indexed data comparing several human-based neural cell types and multiple hydrogel compositions we developed and utilized a Principal Component Analysis (PCA) tool. Based to the analysis, we classified the tested hydrogels and found that

no single hydrogel was optimal. When an interpenetrating network (IPN) hydrogel was synthesized from collagen I (Col1) and hyaluronan-poly (vinyl alcohol) (HA1-PVA) combining the good properties of single hydrogels: the cell supportiveness of the collagen I and the stability of the HA1-PVA, an improved 3D neuronal culture condition was achieved. In conclusion, the HA1-PVA-Col1 IPN hydrogel is a suitable scaffold for human neuronal cells for in vitro models and supports the adhesion formation in 3D.

1. Introduction

Much interest has recently been focused on in vitro models of human organ development and diseases [1]. Especially for studying human central nervous system (CNS) development, function and dysfunctions, in vitro models could offer new insights because the human CNS is very complex and challenging to study in vivo in detail [2-4]. To meet that goal, neurons of human origin should be cultured in a reproducible and reliable manner. Importantly, to better mimic in vivo-like growth and maturation of human neuronal cells in vitro, three-dimensional (3D) cultures with appropriate scaffolds are needed [3]. Various materials have been tested as scaffolds for human pluripotent stem cell (hPSC)-derived neuronal cell-based in vitro models. The crucial aspect of the material selected for these scaffolds is that it allows an interaction between cells and the material that is similar to that in vivo between cells and the extracellular matrix (ECM). Different material properties, including mechanical properties, such as stiffness, material chemistry, availability for binding sites and porosity, affect this interaction [1, 5, 6].

Interactions between neuronal cells and ECM modify not only cell movement and adhesion but also neuronal cell differentiation and maturation [7]. Substrate stiffness is well known to modulate cell behavior in both in vitro and in vivo conditions [8], and more specifically, the 3D environment of ECM or scaffold affects neuronal cell differentiation [9]. In addition, neuronal cell differentiation can be supported by, e.g., electrical conductivity, topography (macro-, micro- or nano-scale), and chemical composition of the scaffold [7]. These physical and chemical features of the scaffold modify cell signaling via adhesion pathways and mechanotransduction. Integrins

are cell membrane-bound proteins mediating these cell-ECM interactions and thus play an important role in cell attachment and behavior [10]. Some of integrins are especially associated with neurons, such as integrin α6β4, which is found to act as a laminin receptor [11]. Moreover, neuronal cells have various specific ECM receptors, such as 40S ribosomal protein SA (RPSA), that have important roles in growth cones [12]. Kinases, which are enzymes that add phosphate groups to other molecules, are very important in these signaling events. ECM receptors are linked to kinase activity that transduces the cellular responses to ECM binding. Some of the best-known kinases are focal adhesion kinase (FAK, also known as protein tyrosine kinase 2 PTK2), mitogen-activated protein kinase/extracellular signal-regulated kinase (MAPK/ERK), and Rho-associated protein kinase (ROCK). FAK is involved in regulating neuronal cell migration and is associated with axon pathfinding both in vivo and in vitro [13]. In neurons, FAK is localized close to nucleus-attaching microtubules, unlike its localization in other cell types [14]. MAPK is crucial in early neuronal cell development and migration and is linked to doublecortin and microtubule protein expression [15]. ROCK also plays an important role in cellular organization during development, and its dysfunctions have been associated with neurodevelopmental disorders [16]. ROCK also limits neurite extension and downregulates transcriptional regulator yes-associated protein 1 (YAP) expression, thus limiting neuronal differentiation and spreading [17]. Therefore, ROCK inhibition plays an important role in neuronal maturation and neurite extension [18]. The active form of YAP in developing neuronal cells maintains proliferation, thus limiting maturation [19]. The stiff substrate (ab. 10 kPa) promotes YAP localization into the nucleus and keeps cells in the self-renewal stage, whereas the soft substrate (ab. 0.7 kPa) results in cytoplasmic YAP localization leading to neuronal differentiation [20].

In summary, several adhesion pathways are associated with neuronal cell growth and maturation. In **Figure 1**, their relations to neurite spreading are shown [17, 20, 21]. Understanding the mechanisms of these regulatory factors in cell differentiation is important when reliable and

efficient in vitro models and novel therapeutic solutions are wanted [22]. In 3D neuronal cultures, a lack of tissue mimicry, which is associated with the 3D architecture and associated degrees of freedom, and the immature stage of hPSC-derived neurons are two main challenges that more careful studies on cell adhesion may help overcome [23-25]. There are several studies in which biomaterials for human neuronal cells have been screened [5], however, the best is yet to be discovered. Even though many natural and synthetic hydrogels seem to provide a suitable 3D environment for human neurons, more research is needed to study their relevant properties for neuronal cell cultures. One strategy is to create a multicomponent hydrogel because ECM is a complex mixture of polymers with many structural subnetworks. These types of hydrogels are called interpenetrating network (IPN) hydrogels [26]. To date, IPN hydrogels consisting of hydrazone crosslinked hyaluronan (HA) combined with collagen have been used to create human mesenchymal stem cell scaffolds [26].

Here, we cultured human neurons derived from three pluripotent stem cell lines in several ECM-mimicking hydrogels, including an IPN hydrogel, and evaluated their performance as a 3D scaffold for human neurons. Neuronal network formation in various hydrogels and hydrogel performance as long-term scaffolds were evaluated with several parameters and analyzed with principal component analysis. In addition, cell adhesion was studied at the gene and protein levels and was associated with neuronal network formation.

2. Experimental Section

2.1. Cells and Differentiation

The following cells/cell lines were used: human neural progenitor cells hNP1 (hNP1; ArunA Biomedicals; Athens, GA, USA), Regea 08/023 human embryonic stem cell (hESC) line (08023; in-house derived), 10212.EURCCs human induced pluripotent stem cell (hiPSC) line (10212; in-house derived) and a primary human foreskin fibroblast cell line ATCC-CRL_2429

(hFF; ATCC; Manassas, Virginia, USA). All experiments were performed under approval from the Finnish Medicines Agency (FIMEA) to perform research using human embryos (Dnro 1426/32/300/05), and supportive statements were obtained from the regional Ethics Committee of Pirkanmaa Hospital District for the derivation, characterization, culture, and differentiation of hESCs (R05116) and the use of hiPSCs in studies (R14023). Both used in-house derived hPSC lines (08023 and 10212) were under quality control with frequent gene and protein expression analysis, karyotype, and mycoplasma assays. Cultures were maintained at +37 °C in a 5 % CO_2 atmosphere and 95 % humidity.

Both in-house-derived hPSC lines (08023 and 10212) were cultured with or without a feeder cell layer of human foreskin fibroblasts (**Supplementary Information 1**) [27, 28] and differentiated to neurons using the neurosphere method as described previously [29]. Neurospheres were cultured in neural differentiation media (NDM). The NDM composition was 1:2 DMEM/F:12 and 1:2 Neurobasal, supplemented with GlutaMax (2 mM), B27 supplement (20 µl ml^{-1}), N2 supplement (10 µl ml^{-1}) (all purchased from Thermo Fisher Scientific, Waltham, MA, USA), penicillin/streptomycin (25 U ml^{-1}; Lonza Group Ltd, Basel, Switzerland) and basic fibroblast growth factor (FGF; 8 µl ml^{-1}; R&D Systems Inc., Minneapolis, MN, USA). LDN193189 (1 mM; STEMCELL Technologies, Cambridge, UK) was used as a promoter of neural differentiation. One third of the medium was changed three times a week, and neurospheres were cut mechanically to a size of 500 µm two times a week. The cells were cultured in suspension culture for 8 weeks to induce neural differentiation prior to the experiments.

HNP1 cells were cultured and expanded according to the manufacturer's instructions, except the medium used, which was made from Neurobasal supplemented with GlutaMax (10 mM; Thermo Fisher Scientific), B27 supplement without vitamin A (20 µl ml^{-1}; Thermo Fisher Scientific), penicillin/streptomycin (25 U ml^{-1}; Lonza Group Ltd) and FGF (8 µl ml^{-1}; R&D Systems Inc.). Briefly, hNP1 cells were plated onto Matrigel-coated (1:200; Corning

Incorporated, Kennebunk ME, USA) dishes, passaged and divided 1:2 or 1:3 when they reached 95-100 % confluence. Twenty-four hours after each passage, the medium was changed and thereafter every other day until confluence. Frozen vials from passages 7-9 of hNP1 cells were thawed rapidly according to the manufacturer's instructions and used in experiments after 1-3 passages, thus in passages 9 or 10.

HFF cells from passage 8 were cultured adherently on T75 bottles in hFF-fetal bovine serum (FBS) medium containing 1X 1MDM (Thermo Fisher Scientific), Pen/Strep (5 µl ml^{-1}; Lonza) and FBS (100 µl ml^{-1}; Sigma-Aldrich, St. Louis, MO, USA).

2.2. Hydrogel Preparation

A total of seven different hydrogels were prepared and used in 3D culture experiments: PuraMatrix (PM; BD Biosciences, San Jose, CA, USA (Catalog No. 354250)/ 3DM Inc., Cambridge, MA, USA; [30]), Gellan Gum (GG; Gelzan™, Sigma-Aldrich; [31]), Collagen hydrogel (Col1), Hyaluronan-Polyvinyl alcohol-based hydrogels (HA1-PVA, HA2-PVA, HA1-PVA-Col), and Hyaluronan-Collagen type I-Poly(ethylene glycol) ether tetrasuccinimidyl glutarate hydrogel (HA-Col1-4SPEG)

2.3.1 Controls

Based on our previous studies and in-house laboratory standards, both positive and negative 3D hydrogel controls were used. The controls were as follows: positive control PM [30] and negative control nonfunctionalized GG [31]. In addition, in-house 2D laboratory standard coating control mouse laminin (Sigma-Aldrich) was used [11]. For PM, cells were mixed with 0.25 % PM diluted in 10 % sucrose in PBS. GG solution (5 mg ml^{-1}) was prepared as previously described [31], and 1.25 % spermidine trihydrochloride (SPD; Sigma-Aldrich) was used as a cross-linker, both dissolved in 10 % sucrose.

2.3.2 First Generation Hydrogels

Aldehyde groups were introduced to HA either by using periodate oxidation (HA1) or selective oxidation of diol-modified HA (HA2). The syntheses and determinations of the degree of substitution (DS %) of modified HA1 and HA2 components were carried out according to our previously reported procedures [32, 33]. Hydrazide groups were introduced to polyvinyl alcohol PVA using glycine ethyl ester and hydrazine as a source of the hydrazide unit. The synthesis and determination of the DS % of the modified PVA component were carried out according to our previously reported procedure [32]. The modified components are presented in **Table 1**.

Two types of HA-PVA hydrogels (HA1-PVA and HA2-PVA) were prepared as previously described [32]. Freeze-dried HA1 or HA2 were dissolved in 10 % sucrose to a concentration of 20 mg ml^{-1}, and PVA was dissolved to a final concentration of 10 mg ml^{-1}. To make a 200 µl hydrazone crosslinked hydrogel, 100 µl of both HA1 or HA2 and PVA were used. HA-Col1-4SPEG hydrogel gelation was performed as described previously [34] but using rat tail collagen type I (Cultrex, Trevigen, Gaithersburg, MD, USA). Col1 hydrogel (0.5 mg ml^{-1}) was prepared by mixing rat tail collagen type I (5 mg ml^{-1}), 10×PBS, sterile H_2O and $NaHCO_3$. For example, to make a 200 µl collagen solution, 20 µl collagen stock was mixed with 20 µl 10×PBS, 157.5 µl sterile H_2O and 2.5 µl $NaHCO_3$.

2.3.3 Second Generation Hydrogel

IPN hydrogel HA1-PVA-Col was prepared by mixing HA1, PVA and neutralized collagen solution in a volume ratio of 2:2:1. The final concentration of collagen was 0.5 mg ml^{-1}. To make 200 µl HA1-PVA-Col gel, HA1 was pipetted in the wells. Then, neutralized and diluted collagen solution was first mixed with PVA, and then the cell suspension was added and mixed. Finally, PVA-Col-cell solution was added and mixed in the well with HA1. Hydrogel formation was confirmed by incubating at 37 °C for 15 min, and then the media was added on top of it.

2.3. Mechanical Testing of Hydrogels

Compression testing was performed as previously described [31, 35], using a BOSE Electroforce Biodynamic 5100 machine equipped with a 225 N load sensor and Wintest 4.1 software (Bose Corporation, Eden Prairie, Minnesota, USA). Briefly, HA1-PVA-Col and HA2-PVA hydrogel samples were cast into a homemade cylindrical mold with an approximate height of 6 mm and a diameter of 12 mm and stored overnight before compression testing to ensure complete gelation. At least five parallel samples of each hydrogel were tested. Unconfined compression was performed with a constant 10 mm min^{-1} strain rate, and samples were compressed until 65-75 % strain was reached from the original height, depending on the fracture point of the material. PM and collagen hydrogels could not, however, be measured because they were too soft to hold their shape.

After compression, the data were analyzed with MS Excel. The data obtained from the stress-strain curve were used to estimate the so-called stiffness of the hydrogels. Because the stress-strain curve of hydrogels (or tissues) is nonlinear in the elastic portion (even at low strains), a polynomial fit was used for the data, and the stiffness of hydrogels was determined according to the previously described method [35].

2.4. Cell Culture

Neurospheres derived from hPSC lines 08023 and 10212 were enzymatically dissociated with 1×TrypLE Select (Thermo Fisher Scientific) into single cells or small aggregates for the hydrogel experiments. Adherently cultured hNP1 cells were detached mechanically according to the manufacturer's instructions into single cells. Additionally, adherently cultured hFF cells were detached with trypsin for the experiments.

In all 3D hydrogel samples, neural cells were encapsulated at a final concentration of $5*10^6$ cells ml^{-1}, while in 2D samples on laminin or on top of the hydrogels, neural cells were plated at a density of 50 000 cells cm^{-2}. Fibroblasts were plated in 2D samples at a density of 10 000 cells cm^{-2}.

Further maturation of neural cells in hydrogels was induced by withdrawing FGF and, in the case of 08023 and 10212 cells, LDN, from the medium. Medium was changed three times a week during the hydrogel experiments. Every cell-hydrogel combination was repeated in two separate experiments, and in every experiment, there were at least 3 parallel sample wells.

2.5. Immunocytochemistry and Imaging

The primary antibodies used targeted β-tubulin III (mouse; 1:1500; Sigma-Aldrich or chicken; 1:4000; Abcam, Cambridge, UK), microtubule-associated protein 2 (MAP2; chicken; 1:4000; Novus Biologicals, Littleton, CO, USA), yes-associated protein (YAP, 63.7; mouse; 1:100; Santa Cruz Biotechnology, Dallas, Texas, USA), CD56 (rabbit; NCAM; 1:800; Merck KGaA, Darmstadt, Germany), vinculin (rabbit; 1:500; Thermo Fisher Scientific), and CD104 (mouse; integrin α6β4; 1:500; Thermo Fisher Scientific). Secondary antibodies conjugated with Alexa 488, 568 or 647 (Thermo Fisher Scientific) were used at a 1:400 dilution, and phalloidin TRITC 568 (Sigma-Aldrich) was used at a 1:800 dilution.

A 3D hydrogel staining protocol optimized previously [31] was used after two or four weeks of cell culture, and the same protocol was also used for 2D controls. Briefly, cells were fixed in 4 % paraformaldehyde for 30 min, and unspecific staining was blocked by 10 % normal donkey serum (NDS), 0.1 % Triton-X 100 and 1 % bovine serum albumin (BSA) (all from Sigma-Aldrich) for 1 h at room temperature. An exception for this was staining for integrin α6β4: blocking, washes and primary antibody solutions were used without Triton-X. Primary antibodies were incubated on cells for 48 h and secondary antibodies for 24 h, both in + 4 °C. Finally, after washes, the cells were mounted with VECTASHIELD containing 4’,6-diamidino-2-phenylindole (DAPI; Vector Laboratories Inc., Burlingame, CA, USA).

The hydrogels were imaged with an Olympus IX51 fluorescence microscope (Olympus Corporation, Japan, Tokyo). The representative samples were imaged with a Zeiss LSM 780 LSCM confocal microscope (Carl Zeiss AG, Oberkochen, Germany).

2.6. Quantitative PCR

Hydrogels were lysed with mechanical disruption by Qiagen PowerLyser with ceramic 2.8 mm PowerBead Tubes (both Qiagen, Hilden, Germany) before obtaining total RNA with a NucleoSpin RNA kit (MACHEREY-NAGEL GmbH & Co, Düren, Germany). To prepare cDNA, 50 ng of total RNA was reverse-transcribed using a high capacity reverse transcription kit. PCR was conducted in reaction mixtures (15 µl) containing 2.5 ng of cDNA, 0.75 µl PCR primers (TaqMan Gene Expression Assay) and 7.5 µl Taq DNA polymerase in PCR buffer on a thermal cycler (7300 Real-Time PCR System). Thermal cycling conditions were as follows: initial incubation at 95 °C for 10 min and 40 cycles of 95 °C for 15 s (annealing) and 60 °C for 60 s (extension). The PCR primers used (TaqMan Gene Expression Assay, Thermo Fisher Scientific) were GAPDH (Assay ID: Hs02786624_g1), MAPK1 (Hs01046830_m1), ROCK1 (Hs01127701_m1), PTK2 (Hs01056457_m1), RPSA (Hs00347791_s1), TUBB3 (Hs00801390_s1) and ITGB4 (Hs00236216_m1).

2.7. Data Processing and Analyses

2.7.1. Imaging Data

The images taken with an Olympus IX51 microscope were processed with Adobe Photoshop CS4 (Adobe Systems Inc., USA, San Jose, CA), and z-stack images acquired with a Zeiss LSM 780 microscope were managed with ZEN microscope software (Carl Zeiss AG). Figures were composed and modified with Adobe InDesign CC (Adobe Systems Inc.).

2.7.2. Indexing of the Neurite Spreading, Cell Adhesion and Gel Performance

To develop a systemic neurite spreading index, all hydrogel samples stained with neuronal markers were semiquantitatively evaluated throughout imaging with an Olympus IX51 microscope. Values from 0 to 3 were given for every sample, where 0 represents cells with no neurite spreading, and 3 represents long and branched neurite structures throughout the hydrogel (**Supplementary Figure 1**). For every cell line, there were at least two separate

experimental repeats, including 1-3 parallel samples for every hydrogel, from which the total neurite spreading index was averaged.

For indexing of adhesion, staining for vinculin, NCAM and integrin α6β4 were semiquantitatively evaluated, and indexing was performed as for neurite spreading (**Supplementary Figure 1**).

To develop an index for gel performance, multiple properties of the gel behavior during the cell culture period were semiquantitatively evaluated (**Supplementary Table 1**). These properties were usability of the gelation procedure, performance of the gelation procedure, usability of cell culturing and performance of the gel after 2 and 4 weeks of cell culturing. Values from 0 to 3 were given accordingly.

2.7.3. Principal Component Analysis

Indexes for neurite spreading, cell adhesion and gel performance as well as results of mechanical testing were further used to classify different hydrogels using principal component analysis (PCA). A more detailed methodology is found in **Supplementary Information 2**. Analysis was performed using MATLAB (2017b, MathWorks, Kista, Sweden), and the results were expressed according to the three most explanatory principal components.

2.7.4. Quantitative PCR Data

QPCR data were analyzed with relative quantification using the comparative quantitation method and are presented as fold differences of ΔCt values. Fold differences were calculated as in **Equation (1)**, where GOI = gene of interest, normalizer = endogenous control/housekeeping gene glyceraldehyde 3-phosphate dehydrogenase (GAPDH). In Figure 7B, values of relative gene expression are represented for integrin α6β4, which are calculated with the ΔΔCt method as in **Equation (2)**, where calibrator = fibroblasts. The efficiency of endogenous control amplification was approximately equal to the amplification of target genes.

$$Ct_{GOI} - Ct_{normalizer} = \Delta Ct, Relative\ Quantity = 2^{-\Delta Ct} \quad (1)$$

$$\Delta Ct_{sample} - \Delta Ct_{calibrator} = \Delta\Delta Ct, Relative\ Quantity = 2^{-\Delta\Delta Ct} \quad (2)$$

2.7.5 Statistical analysis

All quantitative results were formed and statistics were calculated with GraphPad Prism (GraphPad Software, La Jolla, CA, USA). Statistics for the qPCR results were calculated either with unpaired t-test (two sample types comparison) or one-way ANOVA and Tukey's multiple comparison test (three or more sample type comparisons). All quantitative results are reported as the mean ± standard deviation (SD). In all qPCR results, n = 3, and significance in Figures are shown as *: $p < 0.05$, **: $p < 0.01$ and ***: $p < 0.001$.

3. Results and Discussion

3.1. The adhesion of neurons differs from the adhesion of fibroblasts in 2D culture

In most cell adhesion-related studies, fibroblasts have been used as a model cell type [36], whereas the adhesion of neurons has not been widely addressed. Here, cell adhesion of neurons was studied and compared to that of fibroblasts in two dimensions at the gene and protein expression levels. We found that there was a clear difference in the expression of genes related to cell adhesion between neuronal cells and fibroblasts at 1 and 28 days of culture (**Figure 2**). In fibroblasts, the expression of all studied genes (MAPK, ROCK, PTK2, RPSA, ITGB4, TUBB) was already lower than the expression in neurons after one day in vitro and was even lower after 28 days, and the difference was very significant ($p < 0.001$ in all comparisons; Figure 2A, d28). This difference in expression might be because fibroblasts stabilize their migration much quicker and possess contact inhibition after cells have formed enough contacts with each other [37], whereas the neuronal cells used here do not have strong contact inhibition and thus can continue their migration much longer. There are also differences in microtubule organization in fibroblasts and neurons that can affect the organization and expression of microtubule-associated adhesion pathways [38].

Here, we clearly showed that β-tubulin-positive neuronal cells did not express YAP in their nucleus after 28 days of culture on laminin, whereas hFF cells cultured on the same substrate expressed YAP mainly in the nucleus (Figure 2B). This finding is supported by earlier literature [20].

In conclusion, cell adhesion of neurons seems to differ remarkably from the adhesion of fibroblasts. The expression of adhesion markers in these cell types differed by their expression levels both temporally and spatially. Importantly, hFF and neuronal cells behaved very differently on rigid substrates, indicating that their most important adhesion-related pathways differ in those conditions; thus, neuronal adhesion must be studied more specifically.

3.2. The cell source affects neuronal cell adhesion and neurite spreading in two dimensions

Neuronal adhesion has not been widely studied, and the existing results are derived from neuronal cells from various sources. In this study, we utilized three sources for human neurons: hESC- and hiPSC-derived neurons differentiated with the same protocol and commercial hESC-derived NPCs. Interestingly, we found that hiPSC-derived neurons had the highest expression of all studied genes (MAPK, ROCK, PTK2, RPSA and TUBB), which significantly differed from the expression in 0802-3 and hNP1-derived neurons at 28 days of culture on the 2D laminin surface (**Figure 3A**). There were no significant differences between 08023- and hNP1-derived neurons, which were derived from hESCs but produced with different differentiation protocols. However, TUBB expression was significantly higher in 10212-derived neurons. This difference in TUBB expression might indicate a less mature stage of neuronal cells because immature neurons are known to actively remodel their cytoskeleton via a process called the “dynamic instability” of the microtubule network, resulting in a greater need for the growth of neurites and upregulation of β-tubulin [39]. These dynamically instable neurons might also need more expression of adhesion-related genes, which was supported by

the results of this study shown in Figure 3. 10212-derived neurons were seemingly actively finding ways to migrate, as both RPSA (growth cone gene) and ROCK (inhibitor of axonal growth) were upregulated at the same time.

In addition to the differential expression of adhesion markers, neurite spreading and neuronal network formation varied among the neuronal populations derived from different hPSC lines. The 08023-derived neurons had the best neurite and neuronal network forming capacity, while hNP1 and 10212 neurons were less efficient (Figure 3B). Previously, we showed that similarly differentiated hESC and hiPSC neurons do not express ECM- and adhesion-related molecules at the same levels, nor do they form neurites or neuronal networks similarly in different laminin formats [11]. Even though hPSC cell lines have differential initial differentiation capacity despite their origin [40], the differentiation method used does not necessarily make them more similar in their cell type-specific behavior.

In general, both hESC- and hiPSC-derived neuronal cells are valid for building both 2D and 3D in vitro models for particular brain-related diseases [1]. Upcoming studies should examine how similar results can be achieved, for example, in disease modeling between multiple patient-derived cell lines in CNS-related disorders.

As further suggested by our results, one should consider the rather massive variation in the behavior of differentiated cells, whether these differences are cell line- or differentiation protocol-dependent, as the variation can influence the observed results. The most robust conclusions in CNS disorder-related in vitro studies can be made using several relevant human origin cell lines in the same study.

3.3. Evaluation of hydrogel performance using multiple parameter analysis

Here, we evaluated the performance of various hydrogels in supporting 3D neuronal cultures. First, we measured 1) the mechanical properties of hydrogels; then, we used immunostaining to create indexes (explained in Section 2.7.2) for 2) hydrogel performance during gel

preparation and culturing, 3) cell adhesion in 3D and 4) neurite spreading in 3D. These four parameter groups were further combined in PCA analysis to gain an overview of hydrogel performance.

As the stiffness of the 3D scaffold affects neuronal differentiation and maturation, using scaffolds with stiffness values near those of natural brain tissue is reasonable. Mechanical tests performed with the compression method showed that all the studied hydrogels had compression moduli under 10 kPa, which is in the range of brain tissue [31, 32, 35]. The highest measured modulus of the hydrogels used in PCA analysis shown in **Figure 4** was the modulus of GG (1.25 % SPD) at 9.4 ± 2.7 kPa. For others, the modulus was 6.8 ± 2.1 kPa for HA2-PVA and 2.8 ± 0.8 kPa for HA1-PVA. More informative stiffness-strain curves are presented in **Supplementary Figure 2**. The modulus for PM, HA-Col1-4SPEG and Col1 could not be measured with the compression testing method because they were too soft and did not maintain their shape during testing.

Among the gels tested, Col1 best supported neurite spreading (Figure 4A), but it did not perform well in gel performance, as it was reduced in size at 28 days of culture and was difficult to handle (Figure 4B). On the other hand, GG, HA1-PVA and HA2-PVA achieved the best scores in gel performance but did not provide good neurite spreading support (Figure 4B). Details of the hydrogel performance indexes for 28 days are shown in **Supplementary Table 3**. According to the literature, the modulus of collagen type I at low concentrations (1-3 mg ml^{-1}) is under 1 kPa [41, 42], thus being the lowest of all hydrogels studied here. The modulus of HA-Col1-4SPEG could not be measured either, but contrary to Col1, HA-Col1-4SPEG did not support neurite spreading. These results highlight that the mechanical properties of the hydrogel are not necessarily the most important parameters for predicting neural cell growth and neuronal network formation in 3D.

The cell adhesion indexes were combined with ICC staining of vinculin, NCAM and integrin α6β4 and are shown in **Supplementary Table 2**. NCAM is not only a widely used marker for

neuroectodermal and immature neuronal cells [29, 43] but also related to neuronal synapse formation [44]. Vinculin is a link protein between cell adhesion receptors and the actin cytoskeleton, and its expression is increased on focal adhesion points [45]. As mentioned earlier, integrin α6β4 is related to neural cell laminin adhesion [11].

Combining information from different indexes reveals results from a wider perspective, as shown recently [6]. According to the evaluated indexes during the experiments, gel behavior differed between the studied hydrogels both in the case of gel performance properties (gel performance index, Supplementary Table 3) and supportiveness of neurite spreading (neurite spreading index, Supplementary Table 2) (Figure 4B). To combine these indexes with other important parameters, mechanical testing and the neural adhesion index, PCA was performed, and the results clearly separated different culturing conditions into different classes (Figure 4C). PCA analysis classified well-performing gels, PM, Col1, and HA1-PVA, closely together. Moreover, GG and HA2-PVA were clustered closely, both of which were demonstrated to non-supportive gels. HA-Col1-4SPEG formed its own cluster, although a scattered one. Interestingly, laminin 2D controls clearly separated from gel samples, indicating that the 2D surface acts differently from the 3D hydrogels.

We can conclude that the use of more complex analysis methods, such as multiparameter analysis and PCA, can allow more relevant information to be obtained with sufficient time, in line with a recent study [6]. Here, we conclude that Col1 alone was the most supportive scaffold, although it was mechanically unstable.

3.4. Collagen supports neurite spreading of all studied neuronal cells, particularly in three dimensions

Col1 was found to be the most supportive hydrogel for neurite spreading in 3D. Next, we wanted to study how Col1 influences neuronal cell adhesion both on stiff and soft cultures and whether neuronal cells from different cell lines behave differently in those conditions. Here, the

neurite spreading of cells cultured on stiff 2D (laminin), soft 2D (Col1) or soft 3D (Col1) cultures was compared (**Figure 5**). There were no significant differences in neurite spreading indexes between the neurons derived from different hPSC lines or stiff vs. soft culture types, even though neurite spreading of hNP1-derived neurons seemed slightly weaker in 2D cultures (Figure 5B). The immunostaining results showed the same trend (Figure 5A). Additionally, neurite spreading seemed to be more robust and less variable in 3D soft Col1 than in 2D soft Col1 (Figure 5A-B). Overall, the neurite spreading of neurons derived from different hPSC lines was good in Col1.

Neuronal cells cultured in 3D in Col1 expressed all studied adhesion markers despite the original cell line used. Of those, the expression of the adhesion marker RPSA was highest in neurons derived from all different hPSC lines and was significantly higher in 10212 neurons than in 08023- ($p < 0.001$) and hNP1 ($p < 0.05$)-derived neurons. Interestingly, 10212 neurons also had the highest RPSA expression in the 2D laminin substrate (Figure 3A). The neurite spreading index of 10212 neurons compared to that of 08023 neurons may indicate that 10212 neurons are still in an active phase of migration and thus in a less mature stage. Cells that express lesser amounts of β-tubulin might be more mature with already stabilized neurites [39]. Altogether, neurons derived from different hPSC lines are most likely undergoing temporally varying neuronal maturation steps in 3D. Additionally, neuron-specific adhesion marker ITGB4 expression varied among cell lines, being highest in 08023 neurons and lowest in hNP1 neurons.

We conclude that Col1 is a supportive substrate for human neuronal cells in 3D even though it is unstable in long-term (up to 4 weeks) culturing. Longer culturing periods are needed in more sophisticated in vitro models where. for example, electrical properties of neurons are studied because the functional maturation of human neurons is longer than that of rodent neurons in vitro [40].

3.5. Creation of an interpenetrating network (IPN) hydrogel for successful 3D culturing of neurons

From previous results, we found that Col1 was supportive for neurite spreading but an unstable hydrogel for long-term culturing. In contrast, HA1-PVA was stable for long-term culture with moderate support for neurite spreading (Figure 4B). To optimize the 3D scaffold, we generated an IPN gel from HA1-PVA and Col1. IPN gels have previously been used as 3D scaffolds but not with neuronal cells [26]. We tested the HA1-PVA-Col1 IPN gel as a neuronal 3D scaffold. The aim was to combine the supportiveness of Col1 with the stability of HA1-PVA. According to mechanical tests, the compression modulus of HA1-PVA-Col was 1.0 ± 0.3 kPa, which was lower than that of HA1-PVA (2.8 ± 0.8 kPa) but higher than that reported for Col1 (under 1 kPa) in the literature [41, 42]. The IPN hydrogel maintained its shape almost fully for 4 weeks of cell culture (**Figure 6B**). Immunostainings showed that HA1-PVA-Col supported neurite spreading at least as well as Col1 (Figure 6A). Thus, our IPN hydrogel successfully combined the good properties of the gels used. Moreover, we compared the HA1-PVA-Col1 gel with the HA1-PVA gel, Col1 gel and stiff laminin coated (surface with multiparameter PCA analysis combining neurite spreading, gel performance, mechanical testing, and adhesion indexes to see the similarities of the different substrates. According to the PCA results, laminin as a 2D control separated clearly from 3D hydrogels (Figure 6C). Importantly, HA1-PVA-Col was localized very closely together with Col1 and HA1-PVA.

In conclusion, the HA1-PVA-Col1 IPN gel acted as a supportive scaffold material for all used neuronal cell sources and was stable for long-term culturing up to 28 days.

3.6. Integrin α6β4 is an important adhesion marker in neurons

The relationship between the cell adhesion pathways of the neuronal network development process and the effect of 3D hydrogel culture on development are combined during this study. In addition to other adhesion-related molecules, one molecule identified in our previous work

was integrin α6β4 [11]. In the neural field, integrin α6β4 (also known as CD104) has been previously associated mostly with Schwann cells [47], neural stem cell differentiation [21, 48, 49] and pathways regulating cell adhesion, survival and maturation [21]. Integrin α6β4 mediates cell-ECM interactions involving laminin, the protein that is enriched in neural basal lamina [11, 49]. Here, these earlier findings were strengthened, and in addition, integrin α6β4 was shown to be highly expressed in more mature-appearing neuronal cells. In contrast, we could hardly detect any integrin α6β4 expression in human fibroblast cells at the protein or gene level (**Figure 7**). Adhesion can vary greatly between cell types, so the expression of integrin α6β4 was validated here with neurons derived from three different hPSC lines, all of which showed prominent integrin α6β4 expression at the protein level (Figure 7B). The 3D environment, which has previously been associated with a more mature phenotype of neuronal cells [1, 30], also promoted the expression of integrin α6β4 remarkably (Figure 7D).

These findings prove that the adhesion-related regulatory system for neurons is highly different compared with that for fibroblasts. Thus, more intensive research about the specific adhesion mechanisms of neuronal cells is needed.

4. Conclusions

This study highlights the importance of proper study design for in vitro model studies, including choosing relevant cell sources and relevant hydrogel scaffolds and selecting relevant adhesion markers. The findings of this study showed that 1) to build a reliable in vitro model, hPSC cell sources need to be selected carefully and that the use of multiple cell sources is preferable; 2) IPN hydrogels can combine the good properties of used components and thus are a relevant strategy to build more in vivo-like scaffolds for neuronal cells; 3) cell adhesion of neurons differs from that of fibroblasts, and integrin α6β4 is a neuronal cell-specific adhesion marker in both 2D and 3D cultures.

Here, we present a method with which the materials can be valued based on multiple parameters: mechanical testing, neurite spreading, adhesion and gel performance properties. PCA formed from these parameters revealed how different hydrogel scaffolds separate from each other and which scaffold materials resemble each other the most. When summarizing different viewpoints, the HA1-PVA-Col hydrogel was found to be the best for 3D neuronal cell cultures derived from three different cell lines. In the future, this hydrogel can be used in various 3D in vitro studies to better mimic the in vivo growth and maturation of human neurons. This type of study provides new valuable information about neuronal cell types for more successful 3D models and the possibility for transplantation therapies.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Appendix/Nomenclature/Abbreviations

2D	two-dimensional
3D	three-dimensional
BSA	bovine serum albumin
cDNA	complementary DNA
CNS	central nervous system
Col1	collagen type I
DAPI	4’,6-diamidino-2-phenylindole
DS %	degree of substitution
ECM	extracellular matrix
FAK	focal adhesion kinase
FBS	fetal bovine serum

GAPDH	glyceraldehyde 3-phosphate dehydrogenase
GG	gellan gum
GOI	gene of interest
HA	hyaluronan
HA1	HA modified with aldehyde groups by using periodate oxidation
HA1-PVA	hydrogel made of HA1 and PVA
HA2	HA modified by using selective oxidation of diol-modified HA
HA2-PVA	hydrogel made of HA2 and PVA
HA-Col1-4SPEG	HA-Col1-Poly(ethylene glycol) ether tetrasuccinimidyl glutarate
hESC	human embryonic stem cell
hFF	human foreskin fibroblast cell line ATCC-CRL_2429
hiPSC	human induced pluripotent stem cell
hNP1	human neural progenitor cells hNP1
hPSC	human pluripotent stem cell
IPN	interpenetrating network
MAP2	microtubule-associated protein 2
MAPK/ERK	mitogen activated protein kinase/ extracellular-signal-regulated kinase
NCAM	neural cell adhesion molecule
NDM	neural differentiation media
PBS	phosphate-buffered saline
PCA	principal component analysis
PCR	polymerase chain reaction
PM	Puramatrix
PTK2	protein tyrosine kinase 2
PVA	polyvinyl alcohol
ROCK	rho-associated protein kinase

RPSA	40S ribosomal protein SA
SPD	spermidine
YAP	yes-associated protein

Acknowledgements: This research was funded by the Academy of Finland: the Center of Excellence in Body-on-Chip Research (312409 and 312414) and Postdoctoral researcher project (286990), and Business Finland (the Finnish Funding Agency for Innovation) Human Spare Parts project. The authors acknowledge the Tampere Imaging Facility (TIF), the Tampere Facility of iPS Cells and the Tampere CellTech Laboratories for their service.

Keywords: adhesion, human pluripotent stem cells, hydrogel, neurons, tissue engineering

[1] A. M. Hopkins, E. DeSimone, K. Chwalek and D. L. Kaplan, *3D in vitro modeling of the central nervous system,* **125**, 1-25 (2015).

[2] A. R. Maldonado-Soto, D. H. Oakley, H. Wichterle, J. Stein, F. K. Doetsch and C. E. Henderson, *Stem cells in the nervous system,* **93**, 132 (2014).

[3] M. D. Tang-Schomer, J. D. White, L. W. Tien, L. I. Schmitt, T. M. Valentin, D. J. Graziano, A. M. Hopkins, F. G. Omenetto, P. G. Haydon and D. L. Kaplan, *Bioengineered functional brain-like cortical tissue.* **111**, 13811-13816 (2014).

[4] H. N. Hong, J. H. Shim, Y. J. Won, J. Y. Yoo and C. H. Hwang, *Therapeutic time window for the effects of erythropoietin on astrogliosis and neurite outgrowth in an in vitro model of spinal cord injury,* **97**, e9913 (2018).

[5] A. R. Murphy, A. Laslett, C. M. O'Brien and N. R. Cameron, *Scaffolds for 3D in vitro culture of neural lineage cells,* **54**, 1-20 (2017).

[6] H. Tekin, S. Simmons, B. Cummings, L. Gao, X. Adiconis, C. C. Hession, A. Ghoshal, D. Dionne, S. R. Choudhury, V. Yesilyurt, N. E. Sanjana, X. Shi, C. Lu, M. Heidenreich, J. Q. Pan, J. Z. Levin and F. Zhang, *Effects of 3D culturing conditions on the transcriptomic profile of stem-cell-derived neurons,* **2**, 540-554 (2018).

[7] L. M. Y. Yu, N. D. Leipzig and M. S. Shoichet, *Promoting neuron adhesion and growth.* **2008**,*11*, 36-43.

[8] A. M. Cozzolino, V. Noce, C. Battistelli, A. Marchetti, G. Grassi, C. Cicchini, M. Tripodi and L. Amicone, *Modulating the Substrate Stiffness to Manipulate Differentiation of Resident Liver Stem Cells and to Improve the Differentiation State of Hepatocytes*, **2016**, 5481493 (2016).

[9] S. Musah, P. J. Wrighton, Y. Zaltsman, X. Zhong, S. Zorn, M. B. Parlato, C. Hsiao, S. P. Palecek, Q. Chang, W. L. Murphy and L. L. Kiessling, *Substratum-induced differentiation of human pluripotent stem cells reveals the coactivator YAP is a potent regulator of neuronal specification.* **111**, 13805-13810 (2014).

[10] S. Huveneers and E. H. Danen, *Adhesion signaling - crosstalk between integrins, Src and Rho,* **122**, 1059-1069 (2009).

[11] A. Hyysalo, M. Ristola, M. E. Mäkinen, S. Häyrynen, M. Nykter and S. Narkilahti, *Laminin α5 substrates promote survival, network formation and functional development of human pluripotent stem cell-derived neurons in vitro.* **2017**,*24*, 118-127.

[12] R. Cagnetta, C. K. Frese, T. Shigeoka, J. Krijgsveld and C. E. Holt, *Rapid Cue-Specific Remodeling of the Nascent Axonal Proteome,* **99**, 46.e4 (2018).

[13] X. R. Ren, G. L. Ming, Y. Xie, Y. Hong, D. M. Sun, Z. Q. Zhao, Z. Feng, Q. Wang, S. Shim, Z. F. Chen, H. J. Song, L. Mei and W. C. Xiong, *Focal adhesion kinase in netrin-1 signaling,* **7**, 1204-1212 (2004).

[14] S. K. Mitra, D. A. Hanson and D. D. Schlaepfer, *Focal adhesion kinase: in command and control of cell motility,* **6**, 56-68 (2005).

[15] C. Huang, K. Jacobson and M. D. Schaller, *MAP kinases and cell migration,* **117**, 4619-4628 (2004).

[16] A. Reichova, M. Zatkova, Z. Bacova and J. Bakos, *Abnormalities in interactions of Rho GTPases with scaffolding proteins contribute to neurodevelopmental disorders,* **96**, 781-788 (2018).

[17] X. F. Jia, F. Ye, Y. B. Wang and D. X. Feng, *ROCK inhibition enhances neurite outgrowth in neural stem cells by upregulating YAP expression in vitro,* **11**, 983-987 (2016).

[18] K. J. Christie, A. Turbic and A. M. Turnley, *Adult hippocampal neurogenesis, Rho kinase inhibition and enhancement of neuronal survival,* **247**, 75-83 (2013).

[19] W. Xia, Y. Liu and J. Jiao, *GRM7 regulates embryonic neurogenesis via CREB and YAP,* **4**, 795-810 (2015).

[20] S. Musah, P. J. Wrighton, Y. Zaltsman, X. Zhong, S. Zorn, M. B. Parlato, C. Hsiao, S. P. Palecek, Q. Chang, W. L. Murphy and L. L. Kiessling, *Substratum-induced differentiation of human pluripotent stem cells reveals the coactivator YAP is a potent regulator of neuronal specification,* **111**, 13805-13810 (2014).

[21] L. Su, X. Lv, J. Xu, D. Yin, H. Zhang, Y. Li, J. Zhao, S. Zhang and J. Miao, *Neural stem cell differentiation is mediated by integrin beta4 in vitro,* **41**, 916-924 (2009).

[22] L. A. Flanagan, L. M. Rebaza, S. Derzic, P. H. Schwartz and E. S. Monuki, *Regulation of human neural precursor cells by laminin and integrins,* **83**, 845-856 (2006).

[23] M. W. Tibbitt and K. S. Anseth, *Hydrogels as extracellular matrix mimics for 3D cell culture,* **103**, 655-663 (2009).

[24] S. Breslin and L. O'Driscoll, *Three-dimensional cell culture: the missing link in drug discovery*, **18**, 240-249 (2013).

[25] Y. Fang and R. M. Eglen, *Three-Dimensional Cell Cultures in Drug Discovery and Development*, , 247255521769679 (2017).

[26] J. Lou, R. Stowers, S. Nam, Y. Xia and O. Chaudhuri, *Stress relaxing hyaluronic acid-collagen hydrogels promote cell spreading, fiber remodeling, and focal adhesion formation in 3D cell culture*, **154**, 213-222 (2018).

[27] K. Rajala, B. Lindroos, S. M. Hussein, R. S. Lappalainen, M. Pekkanen-Mattila, J. Inzunza, B. Rozell, S. Miettinen, S. Narkilahti, E. Kerkelä, K. Aalto-Setälä, T. Otonkoski, R. Suuronen, O. Hovatta and H. Skottman, *A defined and xeno-free culture method enabling the establishment of clinical-grade human embryonic, induced pluripotent and adipose stem cells.* **5**, e10246 (2010).

[28] H. Hongisto, T. Ilmarinen, M. Vattulainen, A. Mikhailova and H. Skottman, *Xeno- and feeder-free differentiation of human pluripotent stem cells to two distinct ocular epithelial cell types using simple modifications of one method*, **8**, 291 (2017).

[29] R. S. Lappalainen, M. Salomäki, L. Yla-Outinen, T. J. Heikkila, J. A. K. Hyttinen, H. Pihlajamäki, R. Suuronen, H. Skottman and S. Narkilahti, *Similarly derived and cultured hESC lines show variation in their developmental potential towards neuronal cells in long-term culture.* **5**, 749-762 (2010).

[30] L. Ylä-Outinen, T. Joki, M. Varjola, H. Skottman and S. Narkilahti, *Three-dimensional growth matrix for human embryonic stem cell-derived neuronal cells*, **8**, 186-194 (2014).

[31] J. T. Koivisto, T. Joki, J. E. Parraga, R. Pääkkönen, L. Ylä-Outinen, L. Salonen, I. Jönkkäri, M. Peltola, T. O. Ihalainen, S. Narkilahti and M. Kellomäki, *Bioamine-crosslinked gellan gum hydrogel for neural tissue engineering.* **12**, 025014 (2017).

[32] J. Karvinen, T. Joki, L. Ylä-Outinen, J. T. Koivisto, S. Narkilahti and M. Kellomäki, *Soft hydrazone crosslinked hyaluronan- and alginate-based hydrogels as 3D supportive matrices for human pluripotent stem cell-derived neuronal cells*, **124**, 29-39 (2018).

[33] L. Koivusalo, J. Karvinen, E. Sorsa, I. Jönkkäri, J. Väliaho, P. Kallio, T. Ilmarinen, S. Miettinen, H. Skottman and M. Kellomäki, *Hydrazone crosslinked hyaluronan-based hydrogels for therapeutic delivery of adipose stem cells to treat corneal defects*, **85**, 68-78 (2018).

[34] L. Kontturi, E. C. Collin, L. Murtomäki, A. S. Pandit, M. Yliperttula and A. Urtti, *Encapsulated cells for long-term secretion of soluble VEGF receptor 1: Material optimization and simulation of ocular drug response.* **95**, 387-397 (2015).

[35] J. Karvinen, J. T. Koivisto, I. Jönkkäri and M. Kellomäki, *The production of injectable hydrazone crosslinked gellan gum-hyaluronan-hydrogels with tunable mechanical and physical properties*, **71**, 383-391 (2017).

[36] J. T. Parsons, A. R. Horwitz and M. A. Schwartz, *Cell adhesion: integrating cytoskeletal dynamics and cellular tension*, **11**, 633-643 (2010).

[37] D. Ribatti, *A revisited concept: Contact inhibition of growth. From cell biology to malignancy*, **359**, 17-19 (2017).

[38] B. Alberts, A. Johnson, J. Lewis, M. Raff, K. Roberts and P. Walter, *Molecular Biology of the Cell*, Garland Science, 2002.

[39] V. Farina, M. Zedda, M. Bianchi, P. Marongiu and P. L. De Riu, *Tubulin isoforms are differently expressed in developing and mature neurons: a study on the cerebral cortex of newborn and adult rats*, **43**, 285-291 (1999).

[40] S. Toivonen, M. Ojala, A. Hyysalo, T. Ilmarinen, K. Rajala, M. Pekkanen-Mattila, R. Äänismaa, K. Lundin, J. Palgi, J. Weltner, R. Trokovic, O. Silvennoinen, H. Skottman, S. Narkilahti, K. Aalto-Setälä and T. Otonkoski, *Comparative analysis of targeted differentiation of human induced pluripotent stem cells (hiPSCs) and human embryonic stem cells reveals variability associated with incomplete transgene silencing in retrovirally derived hiPSC lines.* **2**, 83-93 (2013).

[41] V.L. Cross, Y. Zheng, N. W. Choi, S. S. Verbridge, B.A. Sutermaster, L.J. Bonassar, C. Fischbach, A. D. Stroock, *Dense type I collagen matrices that support cellular remodeling and microfabrication for studies of tumor angiogenesis and vasculogenesis in vitro*, **31**, 8596-8607 (2010).

[42] J. Joshi, G. Mahajan and C. R. Kothapalli, *Three-dimensional collagenous niche and azacytidine selectively promote time-dependent cardiomyogenesis from human bone marrow-derived MSC spheroids*, **115**, 2013-2026 (2018).

[43] J. Pruszak, K. Sonntag, M. H. Aung, R. Sanchez-Pernaute and O. Isacson, *Markers and methods for cell sorting of human embryonic stem cell-derived neural cell populations*, **25**, 2257-2268 (2007).

[44] L. Bonfanti and D. T. Theodosis, *Polysialic acid and activity-dependent synapse remodeling*, **3**, 43-50 (2009).

[45] J. M. Stukel and R. K. Willits, *Mechanotransduction of Neural Cells Through Cell-Substrate Interactions*, **22**, 173-182 (2016).

[46] M. E. Mäkinen, L. Ylä-Outinen and S. Narkilahti, *GABA and Gap Junctions in the Development of Synchronized Activity in Human Pluripotent Stem Cell-Derived Neural Networks*, **12**, 56 (2018).

[47] L. Su, X. Lv and J. Miao, *Integrin beta 4 in neural cells*, **10**, 316-321 (2008).

[48] L. Su, B. Zhao, X. Lv, N. Wang, J. Zhao, S. Zhang and J. Miao, *Safrole oxide induces neuronal apoptosis through inhibition of integrin beta4/SOD activity and elevation of ROS/NADPH oxidase activity*, **80**, 999-1006 (2007).

[49] T. G. Heintz, R. Eva and J. W. Fawcett, *Regional Regulation of Purkinje Cell Dendritic Spines by Integrins and Eph/Ephrins*, **11**, e0158558 (2016).

Figure 1. Relationships between neurite outgrowth and adhesion-related phenomena based on in vitro studies.

Figure 2. The expression and localization of adhesion-related markers differed between neurons and fibroblasts. A. After d1, the expression of adhesion-related genes MAPK, PTK2 and RPSA was significantly higher in neurons than in fibroblasts (shown here are values of 2^{-dCt}). The expression of all studied adhesion-related genes MAPK, ROCK, PTK2 and RPSA was significantly higher in neurons than in fibroblasts at d28 when cultured on laminin. Moreover, the expression of the ITGB4 gene was significantly higher in neurons both at d1 and d28. Value one represents the level of the housekeeping gene GAPDH for that cell type. Neuronal cells were differentiated from the 08023 cell line. Stars indicate: *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$. B. The adhesion-related marker YAP (red) was localized in the fibroblast nucleus but was not observed in the neuronal nucleus (marked with white arrows) when cells were cultured for 4 weeks on laminin. Staining for β-tubulin + MAP2 (green) is shown for neurons and for DAPI (nuclear stain, blue) for both neurons and fibroblasts. Scale bars are 25 µm.

Figure 3. The expression of adhesion-related genes differed between neurons derived from three different hPSC lines cultured on laminin in 2D. A. The expression of all studied genes (MAPK, ROCK, PTK2, RPSA and TUBB) was significantly higher in 10212 neurons than in either 08023 or hNP1 neurons at the d28 timepoint. Stars indicate: *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$. B. Neurite spreading and neuronal network formation in neurons derived from three different hPSC lines. The neurite spreading and network formation were repeatable between experiments as shown here at d14 for two replicates from different experiments. Staining is for DAPI (blue) and β-tubulin (green). Scale bars are 100 µm.

Figure 4. Neuronal network formation varied between hydrogels in 3D at day 28. A. The most prominent expression of β-tubulin-positive neurites (green) was found in Col1 hydrogels with neurons derived from all three cell lines. DAPI (blue) was used to stain nuclei. The scale bar is 50 µm in all images. B. The combination of two parameters, the gel performance index and neurite spreading index, showed that Col1 had the best influence on neurite spreading, while GG, HA2-PVA and HA1-PVA were better in terms of gel performance. C. Principal component analysis (PCA), including gel performance, adhesion index, neurite spreading index and mechanical testing, clearly classified different culturing conditions into separate clusters. The

most important principal component is shown as PC1, the second important as PC2 and the third as PC3.

Figure 5. The expression of adhesion-related genes and proteins varied between the neurons derived from three different hPSC lines cultured in 3D and between those cultured in 2D and 3D. A. Immunostaining of β-tubulin (green) is shown in all three cell lines cultured for 2 weeks on laminin or on top of Col1 and 4 weeks on laminin or encapsulated in Col1. Counterstaining is for DAPI (blue). Scale bars are 50 µm. B. Neurite spreading indexes from laminin and collagen cultured cells at 2 and 4 weeks. Neurite spreading was widest and most stable for different cell sources with the neurons encapsulated and cultured for 4 weeks in Col1 C. Gene expression of adhesion markers differed between neuronal cells derived from different cell lines in Col1 3D culture at d28. For example, the expression of RPSA was significantly lower in 08023 cells than in the other two cell lines. Stars indicate: *: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$.

Figure 6. The best properties of Col1 and HA1-PVA could be combined by mixing these two hydrogels and preparing an IPN hydrogel of HA1-PVA-Col. A. Immunostainings showing neurite network formation in these three hydrogels. Shown are β-tubulin (green) and DAPI (blue), and scale bars are 50 µm. B. The combination of two parameters, the gel performance index and neurite spreading index, shows that HA1-PVA-Col had good gel performance and better neurite spreading than HA1-PVA. C. PCA revealed how 2D laminin clearly differs from the three tested hydrogels and how HA1-PVA-Col is localized between HA1-PVA and Col1.

Figure 7. Integrin α6β4 is widely expressed in neurons. A. At the protein level, integrin α6β4 was not detectable in 2D cultured fibroblasts (d28). Staining is shown for DAPI (blue), β-tubulin on neurons (green) or phalloidin on fibroblasts (green) and integrin α6β4 (red). B. Relative expression of integrin α6β4 was over 200 times higher in neurons than in fibroblasts at d1 and over 3900 times higher at d28 when cultured on 2D laminin. C. When cultured on top of Col1 for 14 days, integrin α6β4 was expressed in neurons differentiated from all three cell lines. Staining is shown for DAPI (blue), β-tubulin (green) and integrin α6β4 (red). D. Additionally, when cultured in three dimensions in a HA1-PVA-Col gel for 28 days, integrin α6β4 was widely expressed in neurons. Staining is shown for DAPI (blue), integrin α6β4 (green) and phalloidin (red).

Table 1. Modified polymer components of HA1-PVA- and HA2-PVA-based hydrogels.

Polymer	**Supplier**	**Molecular weight [g mol^{-1}]**	**Modified polymer**	**DS%**	**Reference**
HA	Sigma-Aldrich (St. Louis, MO, USA)	1.5-1.8 x 10^6	HA1 (HAALD1H)[a]	5	[32]
HA	Lifecore (Chaska, MN, USA)	1.5 x 10^5	HA2 (HALD1)[b]	15	[33]
PVA	Sigma-Aldrich (St. Louis, MO, USA)	2.7 x 10^4	PVA (PVAHY)[a,b]	13	[32]

[a)] Name according to reference [32]; [b)] Name according to reference [33]; DS% = degree of substitution

Supporting Information

for *Macromol. Biosci.*, DOI: 10.1002/mabi.2013#####

SUPPLEMENTARY MATERIAL

Supplementary Information 1:

Supplementary information for experimental section, pluripotent stem cell culture:

Both in-house derived hPSC lines were cultured with or without feeder cell layer of human foreskin fibroblasts [27, 28] and differentiated as described previously [29]. Passages 23, 34+10FF (feeder free) and 36+5FF of the hESC-line 08023 were used. The maintenance, derivation and characterization of 08023 cell line has been described earlier [28]. 08023 cell line is registered at European Human Embryonic Stem Cell Registry as UTAe007-A (hpscreg.eu/cell-line/UTAe007-A 15.11.2016). Passages 27(20)+5FF, 30(23)+8FF and 32(25)+7FF of the hiPSC-line 10212 were used. Feeder free cultured cells were grown on human recombinant laminin 521 (2 µg cm^{-2}; Biolamina AB, Stockholm, Sweden). After manual cutting of undifferentiated cell colonies, the cells were transferred on to low attachment surface plates and grown as floating aggregates, so called neurospheres, in neural differentiation media (NDM).

Supplementary Information 2:

Principal component analysis:

Principal component analysis (PCA) were used as statistical method to classify the overall performance of different gels according to neurite spreading index, cell adhesion index and gel performance as well as results of mechanical testing. Before PCA, all the data were normalized into same scale (from 0 to 3, maximum value on each parameter were normalized to 3). All the measured values were taken into account in analysis (at least five samples in each group. Different cell lines were pooled together in final results. PCA were performed with MATLAB (2017b, MathWorks, Kista, Sweden) with the followed simple in-house built algorithm:

```
>> expressions= prinCAHPCgels(:,3:6);
expressions = table2array(expressions); %to make simple matrix from table
 subtypes=prinCAHPCgels(:,1);
```

subtypes= table2array(subtypes); % titles for subtypes

>> [coeff, score, latent, tsquared, explained,mu] = pca(expressions); %Principal

%component analysis

X=score(:,1) ; % first component

Y=score(:,2) ; % second component

Z=score(:,3) ; % third component

gscatter3b(X,Y,Z, subtypes, 'bmcr','x...',[10,15,15,15]) ; %3D plot from three main component

Supplementary Figure 1. Example images for different neurite spreading index and adhesion index values from 1 to 3. Values from 1 to 3 are represented from left to right (1: A, D, G, J; 2: B, E, H, K; 3: C, F, I, L) and different staining for neurite spreading (A-C), Integrin α6β4 (D-F), vinculin (G-I) and NCAM (J-L) are from top to bottom. Neurite spreading index is evaluated according to amount of β-tubulin (green) stained network (A-C, J-L), while integrin α6β4 (green, D-F), vinculin (green, G-I) and NCAM (red, J-L) indexes are evaluated comparing their expression to whole staining of neuronal network (β-tubulin). Examples for value 0 are not shown. Scale bar is either 100 µm or 200 µm.

Supplementary Figure 2. Representative stiffness as a function of strain curves for HA1-PVA, HA2-PVA and HA1-PVA-Col hydrogels, and rabbit midbrain tissue. The stiffness-strain-data of HA1-PVA hydrogel and midbrain tissue was obtained from [32].

Supplementary Table 1. Valuation criteria for the gel performance.

	0	**1**	**2**	**3**
Gelation procedure, usability	Gelation could not be performed at all	Difficult and time consuming with multiple critical steps	Quite easy to perform, but multiple steps	Easy to perform, only one or two components, few steps
Gelation procedure, performance	No gelation	Almost liquid gelation product	Gelation product between liquid and solid	Solid gelation product
Cell culturing, usability	Medium could not be changed without destruction of gel	Medium change requires extra carefulness	Medium change requires some carefulness	Medium was easy to change quickly
Cell culturing, performance after 2 weeks	There is no gel left at all	There is only a fraction of gel left	There is smaller gel left than in the beginning	The gel hasn't changed during culturing
Cell culturing, performance after 4 weeks	There is no gel left at all	There is only a fraction of gel left	There is smaller gel left than in the beginning	The gel hasn't changed during culturing

Supplementary Table 2. Neurite spreading index and adhesion indexes. Adhesion indexes include integrin α6β4, vinculin and NCAM values. Values were calculated separately for cells grown on top of hydrogels for 2 weeks or encapsulated for 4 weeks. There were at least two repeats for every adhesion case and six for neurite spreading indexes.

Cells	Gels	Neurite spreading index on top	Integrin α6β4 on top	Vinculin on top	NCAM on top	Neurite spreading index encaps.	Integrin α6β4 encaps.	Vinculin encaps.	NCAM encaps.
hNP1	GG	0.71	1	0.33	1.67	0.63	0.5	0.33	0.33
	PM	1.71	3	0	2.33	2.43	1.5	0	1.67
	HA1-PVA	0	0.5	1	0	0.5	1	0.5	0
	HA2-PVA	0	1	1	0	0.33	0	0	0
	HA-col-4SPEG	0.83	3	2	0.5	0.2	0.5	0.5	0
	Col1	1.17	3	1	2.5	2.67	0.5	0	1.5
	Lam 2w/ 4w	2.1	2.67	2.25	2	1.3	1	0.75	1
08023	GG	0.5	2	0	0.5	1.33	2	1.5	0.5
	PM	2.5	1.5	0.5	2	0.75	0	0	0
	HA1-PVA	0.67	1.5	0.5	1	1.5	2.5	1	0
	HA2-PVA	1.17	1.5	0	0	0.67	0	0	0.5
	HA-col-4SPEG	1.83	3	1	2.5	0.5	1	0	0
	Col1	2.5	3	1	3	2.83	1	1	1
	Lam 2w/ 4w	2.88	2	0	2	2.22	1	1	1.33
10212	GG	0.33	1	0	0	0.67	0.5	0	0.5
	PM	2	1.5	0	2	1.33	0	0.5	0.5
	HA1-PVA	0.17	0	0	0	1.67	0.5	0.5	0
	HA2-PVA	1	1	1	0.5	1	0	0	0
	HA-col-4SPEG	1	1	1	2	1.33	0	0	1
	Col1	1.67	2.5	1.5	1	2.67	1	0.5	0.5
	Lam 2w/ 4w	2.33	2	1.5	2	3	1.5	2	1

Supplementary Table 3. Hydrogel performance indexes when cultured with cells according to criteria presented in Supplementary Table 1.

	Gelation procedure, usability	Gelation procedure, performance	Cell culturing, usability	Cell culturing, performance after 2 weeks	Cell culturing, performance after 4 weeks	Average value
GG	3	2.4	3	2.9	2.8	2.8
PM	2.9	1.6	2.1	1.8	2.3	2.1
HA1-PVA	2.5	2.1	2.9	2.5	2.5	2.5
HA2-PVA	3	2	3	2.6	2.9	2.7
HA-Col-4SPEG	1	1.3	1.4	1.3	1.4	1.3
Col1	2.2	2.3	3	2.6	2.8	2.6