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RESEARCH ARTICLE

Mesenchymal stem cell differentiation in constructs fabricated by three-dimensional bioprinting using a carboxyvinyl polymer-based support material

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Abstract

Three-dimensional (3D) bioprinting using a carboxyvinyl polymer (CVP) solution as a support material, alternately extruded with bioink, holds great promise for tissue engineering and regenerative medicine. This approach enables the fabrication of constructs that are sufficiently soft to preserve the functionality of enclosed cells. To evaluate the applicability of this support material and printing method for mesenchymal stem cells (MSCs), we examined the behavior of immortalized human bone marrow-derived MSCs (UE7T-13). This was carried out with constructs printed using bioinks containing 0.5 w/v% phenol-containing hyaluronic acid, 0.1 w/v% phenol-containing gelatin, and 10 U/mL horseradish peroxidase, which were crosslinked by hydrogen peroxide (H_2O_2) supplied from a support material composed primarily of CVP. During the 14 days of culture after printing, UE7T-13 cells enclosed in the printed constructs elongated and proliferated while maintaining high viability (>90%) and metabolic activity. Furthermore, antibody immunostaining revealed that the cells within the constructs maintained the characteristic MSC phenotype ($CD44^+$ and $CD45^-$). Additionally, following osteogenic, adipogenic, and chondrogenic induction, the cells successfully produced lineage-associated products within the constructs, and the amounts of these products were controlled by varying the H_2O_2 concentration (1–10 mM) in the support material. Overall, the use of CVP together with H_2O_2 in the support material, combined with 3D bioprinting, effectively minimized adverse effects on MSC-associated properties and differentiation potential, while providing a practical strategy for regulating lineage-specific differentiation. These results demonstrate that this method enhances the utility of horseradish peroxidase-containing bioinks and offers great potential for tissue engineering applications.

Keywords: Three-dimensional bioprinting; Support material; Carboxyvinyl polymer; Mesenchymal stem cell; Phenol group

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1. Introduction

Three-dimensional (3D) bioprinting, a technique for fabricating cell-laden hydrogel constructs based on digital designs, has become an essential technology in tissue engineering, regenerative medicine, and drug screening.[1-3] Among the various printing

methods enabled by this technology, extrusion-based 3D bioprinting, which involves extruding a bioink through a nozzle or needle, is among the most widely used.[4,5] It enables the fabrication of multi-ink constructs and offers advantages in terms of compatibility with high-cell-density inks, adaptability to diverse materials, and enhanced cost-effectiveness.[6,7]

In extrusion-based 3D bioprinting, a bioink containing cells is typically deposited layer-by-layer onto a substrate and gelled to form a hydrogel construct.[8] In this printing method, during the fabrication of constructs soft enough to support cellular proliferation and function, the deposited ink tends to deform noticeably under its own weight.[9,10] To address this issue, we previously developed a novel printing method employing a support material alternately extruded with bioink to induce gelation.[11,12] In this method, the support material not only maintains the shape of the extruded bioink but also supplies the chemicals necessary for hydrogelation. This method not only enables the fabrication of constructs from inks that are difficult to print without support materials, but also solves the problem of construct deformation resulting from support material distortion in conventional embedded printing.[11,12] The feasibility of this method in 3D bioprinting has been demonstrated by printing cell-laden constructs with bioinks containing polymers with phenol groups (polymer-Phs).[11,12]

Polymer-Ph solutions are attractive for providing stable hydrogels under physiological conditions through rapid, cell-friendly processes such as enzymatic crosslinking with horseradish peroxidase (HRP)[13,14] and photo-crosslinking with ruthenium (II) tris-bipyridyl dication ($[Ru(bpy)_3]^{2+}$).[15,16] Through these crosslinking methods, cell-laden hydrogels composed of various polymers have been developed, including hyaluronic acid (HA) with phenol groups (Ph),[17,18] alginate,[19,20] chitosan,[21,22] poly(vinyl alcohol),[23,24] gelatin (gelatin-Ph),[25,26] other polysaccharides and proteins,[27-29] and polysaccharide–protein complexes.[14,18,26] By using these polymers as bioink materials in our current printing method that alternately extrudes support materials and bioinks, we have shown that soft constructs capable of supporting cell proliferation can be fabricated.[11,12] Furthermore, the applicability of this printing method to stem cells was demonstrated in a study using a bioink containing polymer-Ph and HRP, along with a support material that supplied the reaction substrate, hydrogen peroxide (H_2O_2).[30]

Bioprinting combined with stem cell technology has attracted attention as a promising approach for tissue engineering and regenerative medicine.[31] Among the various types of stem cells, mesenchymal stem cells (MSCs) are multipotent cells capable of self-renewal and differentiation into multiple cell types, including osteoblasts, chondrocytes, and adipocytes.[32] When applying extrusion-based 3D bioprinting to MSCs, selecting support materials is a critical factor, alongside bioink composition and printing parameters. Differences in osmolarity, residual components, and diffusion properties among various support materials can affect the microenvironment of cells within constructs, with potential implications for stemness maintenance and differentiation behaviors.[31,33] Therefore, evaluating the influence of support-material-assisted bioprinting on the stemness and differentiation potential of MSCs is important in regenerative medicine.

Various support materials have been employed in bioprinting, including carboxyvinyl polymer (CVP) solutions,[34-36] gelatin slurries,[10] and starch slurries.[30] Among these, the CVP solution possesses several advantages, such as cytocompatibility, autoclave sterilizability,[11] tunable rheological properties, and high reproducibility with minimal batch-to-batch variation. To the best of our knowledge, no study has investigated the effects of a CVP solution alternately extruded with bioink as a support material on stem cells.

This study aimed to evaluate the applicability of this printing method to MSCs, in which a CVP solution that promotes gelation is alternately extruded with a bioink. In a previous study on this method, a CVP-based gel for ultrasonographic examinations was supplemented with H_2O_2 and used as the support material, while a solution containing polymer-Ph, HRP, and cells was used as the bioink, and the effects of various factors on printability and cytocompatibility were evaluated.[11] In this study, we employed printing conditions and support materials that achieved both high printability and cytocompatibility; these materials were fabricated using bioinks containing HA-Ph, gelatin-Ph, and immortalized human bone marrow-derived MSCs (UE7T-13) (Figure 1A). UE7T-13 cells are widely used in tissue engineering and regenerative medicine.[37-39] Subsequently, during culture in basal media, the maintenance of MSC-associated properties in the enclosed cells was evaluated based on their survival, morphology, metabolic activity, and mesenchymal phenotypes. Furthermore, during culture in the differentiation medium, the maintenance of differentiation potential was assessed by lineage-specific markers (Figure 1B).

2. Materials and methods

2.1. Materials

HA-Ph (1.5×10^{-4} mol-Ph/g of HA-Ph) and gelatin-Ph (1.3×10^{-4} mol-Ph/g of gelatin-Ph) were synthesized

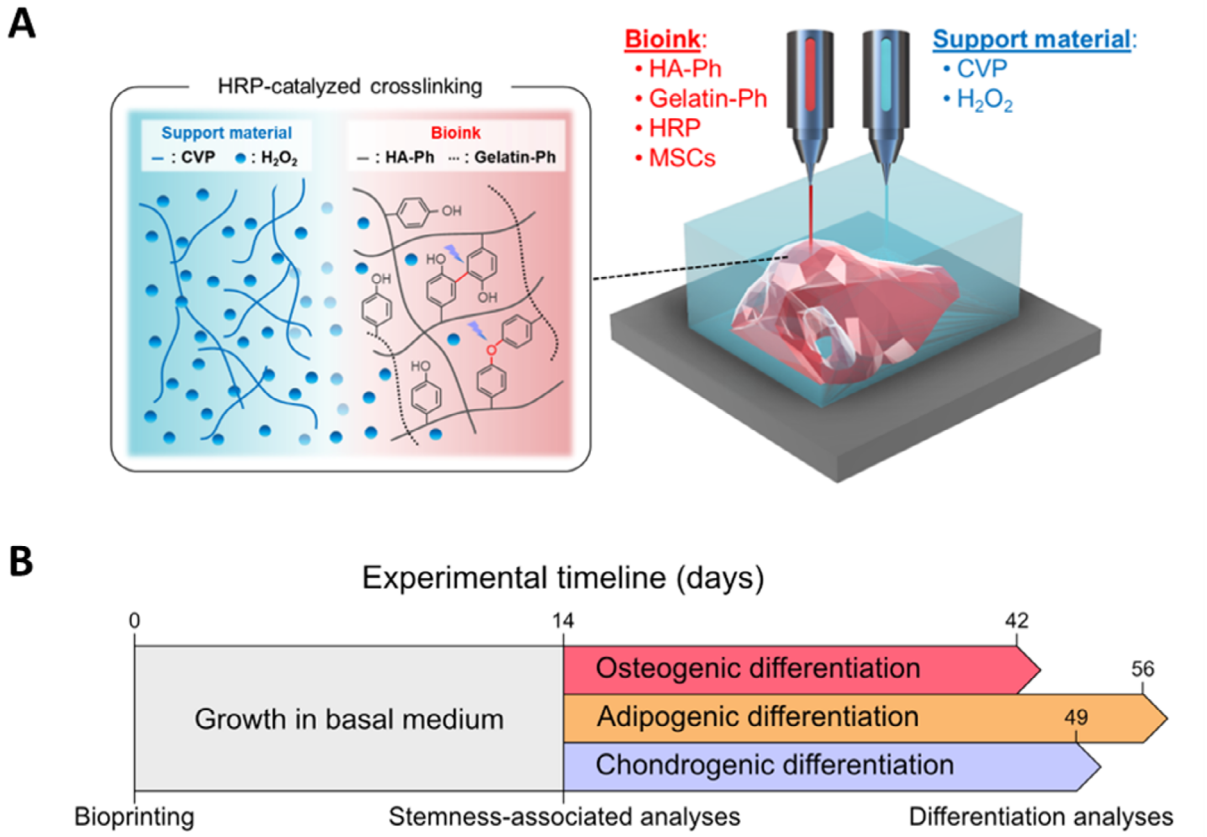


Figure 1. Schematic overview of extrusion-based three-dimensional bioprinting using carboxyvinyl polymer (CVP)-based support material and the experimental timeline. (A) Conceptual illustration of extrusion-based three-dimensional bioprinting using support material containing CVP and hydrogen peroxide (H_2O_2) extruded with bioink containing hyaluronic acid (HA) with phenol groups (Ph), gelatin-Ph, horseradish peroxidase (HRP), and mesenchymal stem cells (MSCs). (B) Experimental timeline for evaluating stemness-associated analyses and osteogenic, adipogenic, and chondrogenic differentiation of UE7T-13 cells enclosed in constructs.

following previously reported methods.[13,40] Tyramine (supplied as tyramine hydrochloride; Chem-Impex, USA) and 3-(4-hydroxyphenyl)propionic acid (Tokyo Chemical Industry, Japan) were respectively grafted onto HA (supplied as sodium HA, HA–LQ, average molecular weight: 850–1600 kDa; Kewpie, Japan) and gelatin (from bovine skin, gel-strength ~225 g Bloom, Type B; molecular weight not specified by the supplier; Sigma-Aldrich, USA), using water-soluble carbodiimide hydrochloride (Peptide Institute, Japan) and N-hydroxysuccinimide (FUJIFILM Wako Pure Chemical, Japan). HRP, H_2O_2 aqueous solution (30 w/w%), hyaluronidase (from ovine testes, 1,110 U/mg), catalase (from bovine liver, 8,000 U/mg), and 4% paraformaldehyde phosphate buffer solution were purchased from FUJIFILM Wako Pure Chemical, Japan. A CVP-based gel for ultrasonographic examinations (Projelly, high-viscosity type; JEX, Japan) was used as the support material. According to the product information provided by JEX (Japan), the solvent in the solution was purified water. The osteogenic differentiation medium was purchased from Cell Applications (USA). Media for adipogenic and chondrogenic differentiation were purchased from Lonza (USA). Calcein-acetoxymethyl (AM) and propidium iodide (PI) were purchased from Nacalai Tesque (Japan) and Dojindo (Japan), respectively.

2.2. Rheological properties

The rheological properties of 0.5 w/v% HA-Ph and 0.1 w/v% gelatin-Ph in phosphate-buffered saline (PBS, pH 7.4) were measured using a rheometer (HAAKE MARS III, Thermo Fisher Scientific, USA) at 25 °C. The viscosity of the solution was measured for 360 s at shear rates ranging from 0.0001 to 1,000 s^{-1} using a parallel-plate rheometer with a 30 mm radius and a 0.5 mm gap.

2.3. Diphenol formation

Diphenol formation in 100 μL hydrogels containing 0.5 w/v% HA-Ph, 0.1 w/v% gelatin-Ph, 0.1–10 U/mL HRP, and 1–10 mM H_2O_2 was measured using a fluorescence plate reader (SpectraMax iD3, Molecular Devices, USA) at approximately 25 °C. Fifteen min after initiating the crosslinking, fluorescence emission spectra from 350 to 600 nm were measured at an excitation wavelength of 310 nm. The peak at approximately 420 nm indicated the formation of diphenol.

2.4. Compressive stiffness of printed constructs

The compressive stiffness of printed constructs (8 mm diameter, 2 mm height) was measured using a material tester (EZ-SX, Shimadzu, Japan) equipped with a 5 N load cell. The constructs were printed using an extrusion-based 3D bioprinter (BioX, Cellink, Sweden) at approximately 25 °C. PBS containing 0.5 w/v% HA-Ph, 0.1 w/v% gelatin-Ph, and 0.1–10 U/mL HRP was used as the ink. CVP-based gel containing 2.0 w/w% CVP and 1 or 10 mM H_2O_2 was used as the support material. The ink and support material were extruded from 27-gauge tapered nozzles at 2.8 μL/s. The thickness of each layer was set to 0.3 mm (0.2 mm for the first layer). Five min after printing, the support material was removed from the constructs. Young's modulus was calculated from the slope of the stress–strain curve in the strain range of 1–10% during compression at 6 mm/s using an 8 mm probe.

2.5. Cell culture

Immortalized human bone marrow-derived MSCs (UE7T-13, Riken Cell Bank, Japan) were grown in Dulbecco's Modified Eagle Medium (DMEM; Shimadzu, Japan) containing 10 v/v% fetal bovine serum and 1 g/L glucose in a humidified 5% CO_2 incubator at 37 °C.

2.6. Three-dimensional bioprinting with cells

A 3D bioprinter was used to print cell-laden constructs (1 mm width, 1 mm height) (Figure S1). HA-Ph and gelatin-Ph were sterilized via ethanol treatment, dried, and dissolved in PBS overnight. Immediately before printing, HRP and UE7T-13 cells were added to the polymer solution to prepare the bioink containing 0.5 w/v% HA-Ph, 0.1 w/v% gelatin-Ph, 10 U/mL HRP, and 1×10^6 cells/mL UE7T-13 cells. The support materials were prepared by supplementing autoclaved CVP-based gel containing 2.0 w/w% CVP with H_2O_2 to final concentrations of 1 or 10 mM. The H_2O_2 solution used in this study was a commercially available 30 w/w% aqueous solution, added aseptically to the autoclaved CVP-based gel. No additional sterilization was performed for the H_2O_2 solution. Using the nozzles and layer thickness described in Section 2.4, the bioink and support material were extruded at 5.2 and 1.6 μL/s, respectively. After removal of the support material 5 min after printing, the constructs were incubated overnight in 2 mL of culture medium containing 1 mg/mL catalase to degrade the remaining H_2O_2 to water and oxygen. Thereafter, the medium was replaced with 2 mL of catalase-free culture medium.

2.7. Live/dead staining

Cells in the constructs were stained with Calcein-AM and PI at final concentrations of 1.0 μg/mL each on days 1, 7, and 14 after printing. Stained cells were observed under a fluorescence microscope (APX-100, Olympus, Japan).

2.8. Mitochondrial activity

Mitochondrial activity in the constructs was assessed using a WST-8 reagent (Cell Count Reagent SF, Nacalai Tesque, Japan) at 1, 7, and 14 days after printing. The cell-laden constructs were incubated in DMEM containing 10 v/v% of the reagent at 37 °C for 3 h. After incubation, mitochondrial activity was quantified by measuring the absorbance at 450 nm using an ultraviolet (UV)–visible (Vis) spectrometer (UV-2600, Shimadzu, Japan).

2.9. Flow cytometry

Flow cytometry of cells within the constructs was conducted to assess CD44 and CD45 expression 14 days after printing. The cells were collected by degrading the constructs with incubation in DMEM containing 0.1 w/v% hyaluronidase at 37 °C for 1.5 h. Then, the aggregates of the collected cells were dissociated by incubation in a 0.1 w/v% trypsin solution at 37 °C for 10 min. The cells were stained with Calcein-AM, then incubated in a solution containing Human TruStain FcX™ (BioLegend, USA) at approximately 25 °C for 10 min. Finally, the cells were stained with PerCP/Cyanine5.5-conjugated anti-mouse/human CD44 (BioLegend, USA) and BD Horizon™ PE-CF594-conjugated mouse anti-human CD45 (BD Biosciences, USA) for 30 min at 4 °C. Flow cytometry was conducted using a flow cytometer (CytoFLEX, Beckman Coulter, USA).

2.10. Osteogenic, adipogenic, and chondrogenic differentiation induction

Osteogenic, adipogenic, and chondrogenic differentiation of cells in the constructs was induced by replacing DMEM with the corresponding differentiation media 14 days after printing.

2.11. Alizarin Red staining

Alizarin Red staining was performed 14 and 28 days after the initiation of osteogenic differentiation. The

cells in the constructs were fixed with paraformaldehyde at approximately 25 °C for 30 min. Subsequently, the calcium deposits in the constructs were stained with water containing 40 mM Alizarin Red S (FUJIFILM Wako Pure Chemical, Japan) for 1 h, followed by washing with water. The calcium deposits were observed using a microscope (APX-100, Olympus, Japan).

2.12. Alkaline phosphatase activity

The alkaline phosphatase (ALP) activity of cells in the constructs was measured at 1, 14, and 28 days after the initiation of osteogenic differentiation, following a previously reported method.[30] After collection, as described in Section 2.9, the cells were lysed with 50 mM 2-amino-2-methyl-1-propanol buffer containing 0.1 v/v% Triton X-100 (Nacalai Tesque) at 4 °C for 10 min. After centrifugation at 12,000 × g for 10 min at 4 °C, lysates were incubated with 5 mM disodium p-nitrophenyl phosphate (FUJIFILM Wako Pure Chemical, Japan) in 2-amino-2-methyl-1-propanol buffer at 37 °C for 1 h. The resulting p-nitrophenolate (pNP) concentration was determined from the absorbance at 405 nm using a UV–Vis spectrometer.

2.13. Oil Red O staining

Oil Red O staining was performed at 7, 24, and 42 days after the initiation of adipogenic differentiation. After fixing the cells as described in Section 2.11, lipid droplets in the constructs were stained with a 60 v/v% 2-propanol solution containing 0.3 w/v% Oil Red O (Sigma-Aldrich, USA) for 30 min, followed by washing with a 60 v/v% 2-propanol solution. Lipid droplets were observed under a microscope.

2.14. Alcian blue staining

Alcian blue staining was performed at 21 and 35 days after the initiation of chondrogenic differentiation. After fixing the cells as described in Section 2.11, sulfated glycosaminoglycans in the constructs were stained with Alcian blue solution (FUJIFILM Wako Pure Chemical, Japan) for 30 min, followed by washing with hydrochloric acid solution. Glycosaminoglycans were observed under a microscope.

2.15. Structural stability of constructs

Structural stability was evaluated based on construct width retention during culture. Digital images were acquired at the indicated time points, and the average width of six sides was normalized to the value for the same construct on day 1.

2.16. Statistical analysis

The quantitative data are expressed as means ± standard deviation. Microsoft Excel for Microsoft 365 MSO (Version 2605, Microsoft, USA) was used for the statistical data analysis. Data were analyzed using one-way analysis of variance with Tukey's Honest Significant Difference test. Differences were considered significant if the p-value was < 0.05.

3. Results and discussion

3.1. Evaluation of viability, morphology, and proliferation of stem cells in a printed construct

We fabricated constructs containing UE7T-13 cells using a printing method that alternately extruded a bioink and a support material containing CVP and 1 mM or 10 mM H_2O_2, and evaluated the viability, morphology, and proliferation of the enclosed cells. Fluorescence microscopy showed that most Calcein-AM-stained cells exhibited green fluorescence over 14 days after printing (Figure 2A). On day 1 of culture, the cells displayed a predominantly round morphology; however, from day 7 onward, they adopted an elongated shape (Figure 2A). Furthermore, mitochondrial activity per construct increased during the 14 days of culture (Figure 2B). Additionally, there were no significant differences in cell survival, morphology, or mitochondrial activity within the constructs printed with support materials containing 1 and 10 mM H_2O_2. These results indicate that, in constructs printed with both H_2O_2 concentrations, cells elongated and proliferated while maintaining high viability and metabolic activity. Because construct properties can affect cell behavior, we characterized their compressive stiffness and diphenol formation. At 10 U/mL HRP, increasing the H_2O_2 concentration from 1 to 10 mM significantly increased Young's modulus from 1.3 ± 0.5 to 4.2 ± 1.8 kPa ($p < 0.05$, $n = 3$; Figure S2). In contrast, decreasing the HRP concentration to 0.1 U/mL reduced Young's modulus (Figure S2). Higher HRP and/or H_2O_2 concentrations also increased diphenol formation (Figure S3), consistent with previous reports.[11,41] These results suggest that the increased reaction rate at higher HRP concentrations and the greater H_2O_2 supply increased the crosslinking density of the constructs. Despite the increase in Young's modulus at higher H_2O_2 concentrations, the constructs remained sufficiently soft to allow cell elongation and proliferation. The observed cell elongation and proliferation are consistent with previously reported studies on UE7T-13 cells enclosed in hydrogels containing polymers with cell-adhesive motifs, such as gelatin, and characterized by

mechanical properties too weak to support self-standing structures.[30] In addition to the cell adhesiveness and low mechanical properties of the constructs, the use of a low-viscosity pseudoplastic bioink (Figure S4) similar to that employed in previous studies,[11,12] is thought to reduce the mechanical stress, including shear stress and pressure, on the cells during extrusion. This is particularly important for MSCs because of their sensitivity to such mechanical stimuli.[42] Overall, these results suggest that the printing method involving a support material containing CVP and H_2O_2 was compatible with MSCs and provided sufficiently soft constructs that supported cell survival, elongation, and proliferation.

3.2. Evaluation of mesenchymal phenotype

We evaluated the effects of a printing process involving support materials containing CVP and H_2O_2, followed by 14 days of in situ culture within the constructs, on the mesenchymal phenotype of UE7T-13 cells. As indicated in Section 3.1, cells were exposed to mechanical stress caused by extrusion and chemical stress from CVP and H_2O_2. Furthermore, the microenvironment within constructs may limit the diffusion of nutrients and oxygen. It has been suggested that these mechanical and chemical stresses, as well as the microenvironment characterized by low nutrient levels and hypoxia, affect the natural phenotypes of MSCs.[42-44] CD44 was selected as a positive marker to confirm the maintenance of the mesenchymal phenotype. CD44 plays a role in maintaining stem cell properties by binding to HA and promoting its adhesion, migration, and self-renewal.[45] Therefore, a decrease in CD44 expression indicates a deviation from the natural MSC phenotype. Additionally, the hematopoietic marker CD45 was selected as a negative marker, as it is a standard flow cytometry marker used in combination with CD44 to confirm MSC maintenance.[32,33,46]

In both fluorescence imaging and flow cytometry, fluorescence derived from immunostained CD44 was observed on the surfaces of cells cultured in dishes and within the constructs (Figure 3A and 3B). In contrast, no CD45 fluorescence was observed (Figure 3A and 3C). Furthermore, the flow cytometry results indicated that cells cultured within the constructs exhibited higher CD44 expression than those cultured in dishes (Figure 3B). This increase in CD44 expression is thought to result from the interaction between HA in the construct and the cell surface.[47,48] However, no increase in CD44 expression was observed in UE7T-13 cells cultured in a hydrogel that did not contain HA.[30] Taken together with the results in Section 3.1, these findings indicate that the printing process using a support material containing CVP and H_2O_2 had no significant adverse effects on MSC-associated properties, including their natural morphology, proliferation potential, and phenotype. Furthermore, the enclosed MSCs were maintained undifferentiated for 14 days after printing.

3.3. Evaluation of osteogenic differentiation

To confirm that the UE7T-13 cells retained their differentiation potential even after 14 days of culture in the

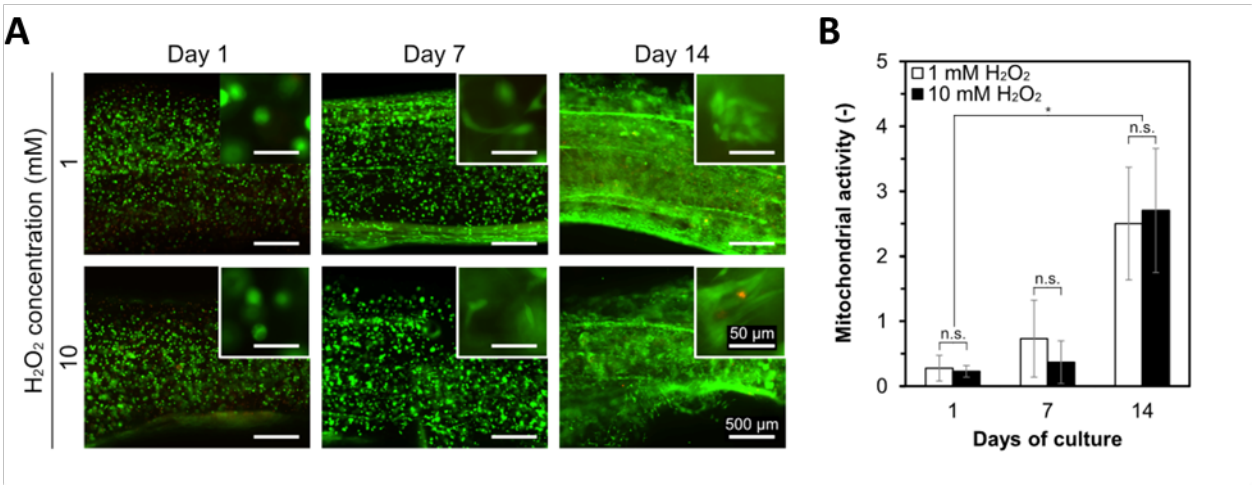


Figure 2. Viability, morphology, proliferation, and mitochondrial activity of UE7T-13 cells in constructs. (A) Fluorescence images. Scale bars: 500 μm, 50 μm; magnification: 2 ×, 5 ×. (B) Mitochondrial activity of UE7T-13 cells within constructs containing 0.5 w/v% hyaluronic acid-phenol and 0.1 w/v% gelatin-phenol on day 1, 7, and 14 of culture. The cells were stained using Calcein-acetoxymethyl (green: live cells) and propidium iodide (red: dead cells). The concentrations of horseradish peroxidase in the bioink, carboxyvinyl polymer, and hydrogen peroxide (H_2O_2) in the support material were 10 U/mL, 2.0 w/w%, and 1–10 mM, respectively. Error bars indicate standard deviation ($n = 3$). Notes: *$p < 0.05$, Tukey's Honest Significant Difference test; n.s.: No significant difference ($p > 0.05$).

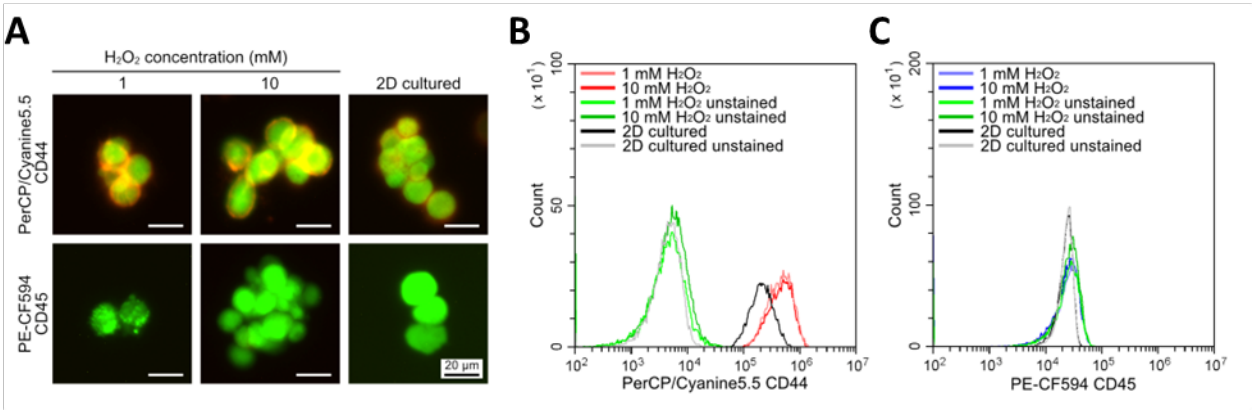


Figure 3. CD44 and CD45 expression in bioprinted UE7T-13 cells evaluated by fluorescence imaging and flow cytometry. (A) Fluorescence images. Scale bars: 20 μm; magnification: 5×. (B, C) Flow cytometry of UE7T-13 cells immunostained with CD44-PerCP/Cyanine 5.5 and CD45-PE-CF594. The cells were cultured in constructs or dishes for 14 days after printing and stained with Calcein-acetoxymethyl. The concentrations of horseradish peroxidase in the bioink, carboxyvinyl polymer, and H_2O_2 in the support material were 10 U/mL, 2.0 w/w%, and 1–10 mM, respectively.
Abbreviations: 2D: Two-dimensional; H_2O_2: Hydrogen peroxide.

constructs, we evaluated their osteogenic differentiation potential. Osteogenic differentiation was induced for 28 days by replacing the basal medium with the differentiation induction medium on day 14 (Figure 1B). Osteogenic differentiation was evaluated using Alizarin Red staining and ALP activity.

In constructs fabricated with support materials containing 1 and 10 mM H_2O_2, calcium deposition stained with Alizarin Red was observed throughout the constructs by day 14 of differentiation induction, and the staining intensity showed little change thereafter (Figure 4A). This result indicated that calcium deposition progressed rapidly during the first 14 days of induction and subsequently plateaued. The deposits exhibited a nodular morphology, consistent with the characteristics reported in previous studies on the osteogenic differentiation of UE7T-13 cells.[38,49] No calcium deposition was observed in non-induced cells even after 42 days of culture (Figure 4B). In addition to calcium deposition, we evaluated ALP activity, a marker of osteogenic differentiation essential for calcification. ALP hydrolyzes phosphate esters to produce inorganic phosphates for hydroxyapatite formation. ALP activity per cell was assessed by measuring the absorbance of pNP, which is generated from p-nitrophenyl phosphate, after normalization to the total protein content. In cells subjected to osteogenic induction for 14 days, the absorbance of pNP was higher than that in non-induced cells (Figure 4C). Furthermore, pNP absorbance increased further when induction was continued for 28 days. In contrast, the absorbance of non-induced cells did not change even after 42 days of culture (Figure 4C). These results indicate that ALP activity was higher in differentiation-induced cells than in non-induced cells and continued to increase throughout the induction period. Furthermore, from day 14 of induction onward, the constructs printed with 1 mM H_2O_2 exhibited higher ALP activity than those printed with 10 mM H_2O_2 (Figure 4C).

The continued increase in ALP activity in UE7T-13 cells even after 14 days of differentiation induction, despite the absence of further expansion of the mineralized area, suggests that matrix maturation and mineralization processes remained active after the initial mineral deposition stage. Furthermore, the higher ALP activity observed in constructs printed at lower H_2O_2 concentrations is thought to be due to the lower crosslinking density, which provided a more permissive environment for cell elongation. Previous studies have shown that ALP activity increases in hydrogels with higher porosity and softer mechanical properties, allowing cells to elongate.[50,51] Overall, these results from Alizarin Red staining and ALP activity measurements demonstrate that the 3D printing processes using support materials containing CVP and H_2O_2, as well as the culture period prior to differentiation induction, did not compromise the osteogenic potential of UE7T-13 cells or cause any unintended differentiation. Furthermore, these findings indicate that controlling H_2O_2 concentration enables modulating the crosslinking density of the constructs and the cellular microenvironment, thereby regulating osteogenic differentiation.

3.4. Evaluation of adipogenic differentiation

We evaluated the adipogenic differentiation potential of UE7T-13 cells using these constructs. Adipogenic differentiation was induced using a differentiation medium from day 14 after printing and continued for 42

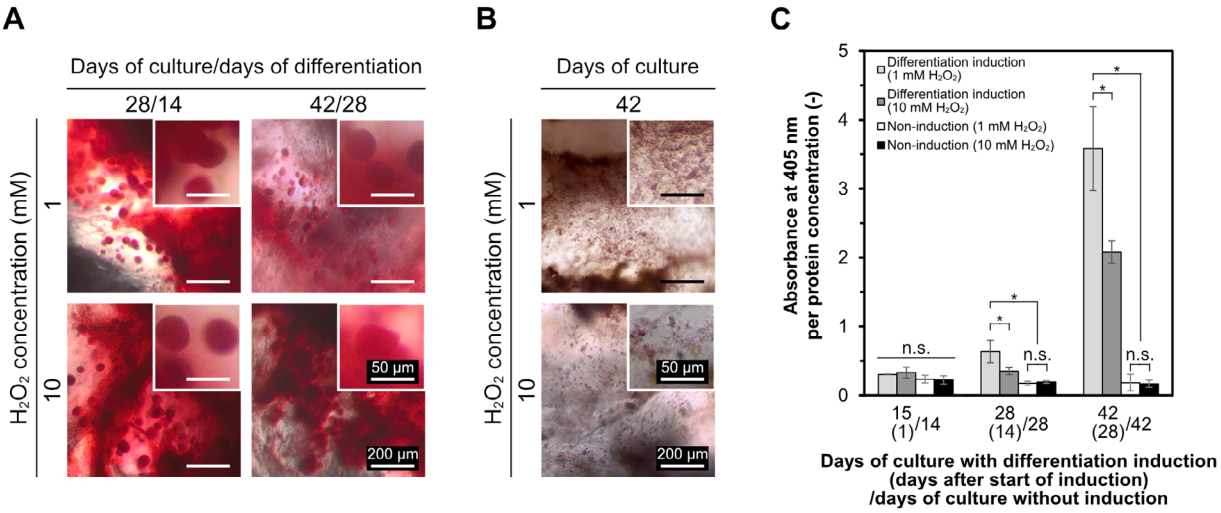


Figure 4. Assessment of osteogenic differentiation of the cells: Alizarin Red staining (A) with and (B) without differentiation induction (scale bars: 200 μm, 50 μm; magnification: 2×, 5×), and (C) alkaline phosphatase activity measured using cell lysates adjusted to a final protein concentration of 1 mg/mL. Differentiation was conducted after an initial 14 days of enclosure. The concentrations of horseradish peroxidase in the bioink, carboxyvinyl polymer, and hydrogen peroxide (H_2O_2) in the support material were 10 U/mL, 2.0 w/w%, and 1–10 mM, respectively. Notes: *$p < 0.05$, Tukey's Honest Significant Difference test; Error bars: standard deviation ($n = 3$); n.s.: no significant difference ($p > 0.05$).

days (Figure 1B). On days 7, 24, and 42 after induction, adipogenic differentiation was evaluated by observing the lipid droplets associated with adipocyte differentiation using Oil Red O staining, the most common staining method for adipogenically differentiated MSCs.[42] On day 7 of induction, lipid droplets with diameters of less than 10 μm were observed, indicating the initiation of adipogenic differentiation (Figure 5A). By day 24, some lipid droplets reached 10 μm or more in diameter and formed aggregates in parts of the constructs. On day 42, they were distributed throughout the construct. These results indicated that the UE7T-13 cells enclosed in the constructs retained their adipogenic differentiation potential, successfully differentiated into the adipocyte lineage, and continued to undergo adipogenesis through day 42. In contrast, cells cultured in a basal medium for the same period formed almost no lipid droplets (Figure 5B). This result suggests that unwanted differentiation was not initiated by the printing process or cultivation within the construct before the induction of differentiation. Furthermore, on day 42, larger and more coalesced lipid droplets formed in the construct printed using a support material containing 1 mM H_2O_2 than in the construct printed using 10 mM H_2O_2. This result is consistent with previous reports and suggests that adipocyte differentiation is promoted by softer constructs.[52] Overall, these results demonstrate that the printing process minimized adverse effects on the ability of cells to differentiate into adipocytes. As in the case of osteogenic differentiation described in Section 3.3, adjusting the H_2O_2 concentration can serve as a practical strategy for fabricating soft constructs that promote adipogenic differentiation.

3.5. Evaluation of chondrogenic differentiation

We evaluated the chondrogenic differentiation potential of the UE7T-13 cells enclosed in these constructs. Chondrogenic differentiation was induced with chondrogenic differentiation medium from day 14 following printing, continued for 35 days, and evaluated by observing the sulfated glycosaminoglycans produced via Alcian blue staining on days 21 and 35 after induction (Figure 1B). Alcian blue-stained microscopic aggregates were observed within the constructs on day 21, indicating the initial deposition of sulfated glycosaminoglycans (Figure 6A). Furthermore, by day 35, both the stained area and staining intensity increased, indicating the progression of glycosaminoglycan deposition. In contrast, no deposition was observed when the cells were cultured in a basal medium for the same period (Figure 6B). These results indicate that, as with osteogenesis and adipogenesis, the printing process and culturing within the construct prior to differentiation induction did not cause unintended differentiation before induction. Constructs printed using 1 mM H_2O_2 exhibited higher staining intensity at both time points than those printed using 10 mM, suggesting enhanced glycosaminoglycan formation in constructs with a lower crosslinking density. Consistent with previously reported findings, this result suggests that chondrogenic differentiation was enhanced in constructs with lower crosslinking density.[53] Based on these results, similar to

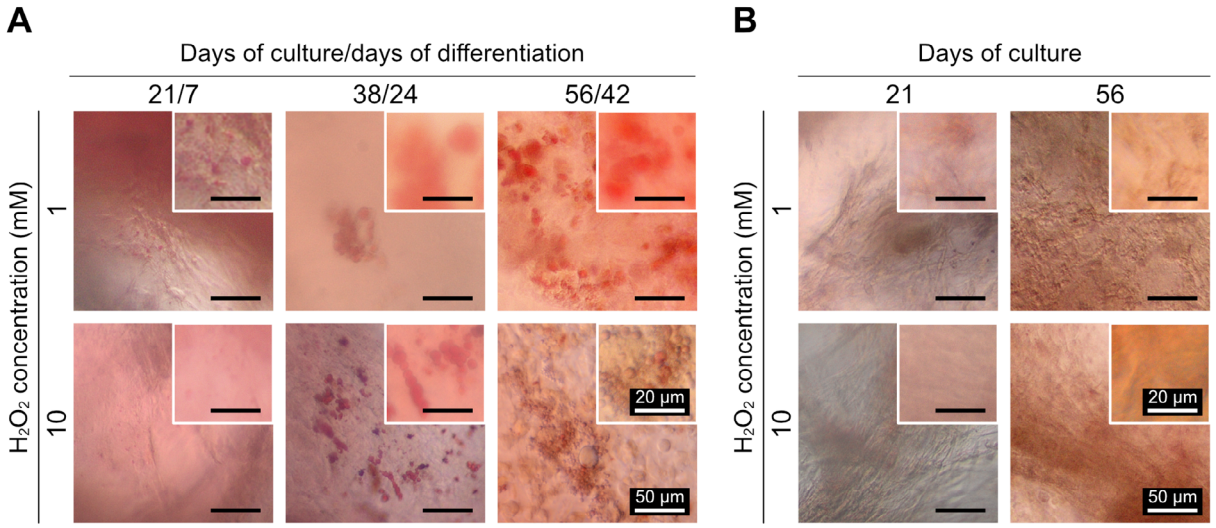


Figure 5. Adipogenic differentiation of UE7T-13 cells enclosed in constructs containing 0.5 w/v% hyaluronic acid-phenol and 0.1 w/v% gelatin-phenol. Micrographs of lipid droplets stained with Oil Red O (A) with and (B) without differentiation induction. Scale bars: 50 μm, 20 μm; magnification: 5×, 20×. Differentiation induction was started 14 days after bioprinting. The concentrations of horseradish peroxidase in the bioink, carboxyvinyl polymer, and hydrogen peroxide (H_2O_2) in the support material were 10 U/mL, 2.0 w/w%, and 1–10 mM, respectively.

the findings for osteogenic and adipogenic differentiation, this printing process preserved the chondrogenic differentiation potential of UE7T-13 cells and demonstrated that the modulation of H_2O_2 concentration could regulate lineage-specific microenvironments for chondrogenic differentiation.

3.6. Structural stability of constructs

Structural stability was evaluated by measuring construct width during culture and normalizing it to its width on day 1. Regardless of cell presence, the constructs did not collapse in the culture medium during the 14-day culture period, and their widths remained unchanged. However, deformation was observed only in the cell-laden constructs on day 14 (Figure 7A–C). This was likely due to an increase in tensile force associated with cell proliferation.[54,55] The construct deformed more markedly during osteogenic differentiation induced from day 14 after printing and shrank significantly (Figure 7D). This shrinkage is thought to result from increased actomyosin contractile force and cytoskeletal tension associated with osteogenic differentiation. No further shrinkage was observed after 14 days of osteogenic induction. This result is likely due to the rapid progression of osteogenic differentiation in UE7T-13 cells during the first 14 days of induction, which is consistent with the calcium deposition results described in Section 3.3. In contrast, constructs undergoing chondrogenic differentiation exhibited less deformation than those subjected to osteogenic differentiation. This deformation was further reduced in constructs printed with support materials containing 10 mM H_2O_2, which produced a higher crosslinking density than those printed with 1 mM H_2O_2 (Figure 7D). Furthermore, the deformation was smaller during adipogenic differentiation (Figure 7D). This is consistent with previous studies, which showed that adipogenic differentiation does not markedly increase cellular tensile force, whereas chondrocyte tensile force is higher than that of adipocytes but lower than that of osteocytes.[56] Overall, the results demonstrated that during the 14-day culture period prior to differentiation induction, the constructs remained structurally stable and similar to those without cells. In contrast, subsequent differentiation induction causes deformation consistent with lineage-dependent cellular contractility.

3.7. Advantages, limitations, and future research

One advantage of this printing method is that H_2O_2 is spatially separated from the cell-laden bioink before extrusion. Because the direct addition of H_2O_2 to polymer-Ph/HRP inks can cause gelation before extrusion, H_2O_2 delivery from the CVP-based support material allows the bioink to remain printable while inducing crosslinking after deposition.[30] In this system, the support material therefore functions both as a temporary structural support and as an H_2O_2 supplier.

Compared to our previous studies using this printing method,[11] the present study focuses on the behavior of MSCs within printed constructs. By evaluating cell morphology, proliferation, mesenchymal phenotype, and

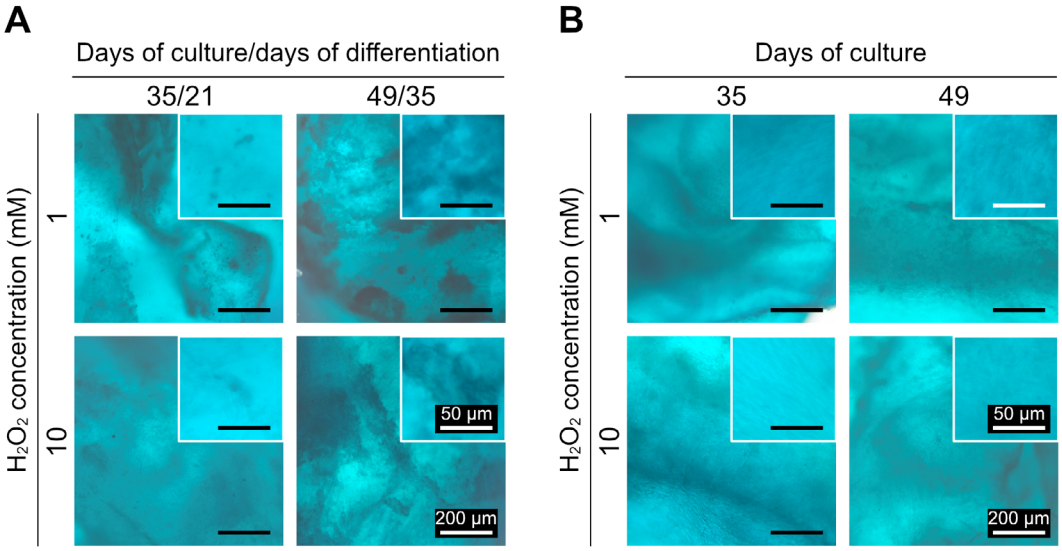


Figure 6. Chondrogenic differentiation of UE7T-13 cells enclosed in constructs containing 0.5 w/v% hyaluronic acid-phenol and 0.1 w/v% gelatin-phenol. Micrographs of sulfated glycosaminoglycans stained with Alcian blue (A) with and (B) without differentiation induction. Scale bars: 200 µm, 50 µm; magnification: 5×, 20×. Differentiation induction was started 14 days after bioprinting. The concentrations of horseradish peroxidase in the bioink, carboxyvinyl polymer, and hydrogen peroxide (H_2O_2) in the support material were 10 U/mL, 2.0 w/w%, and 1–10 mM, respectively.

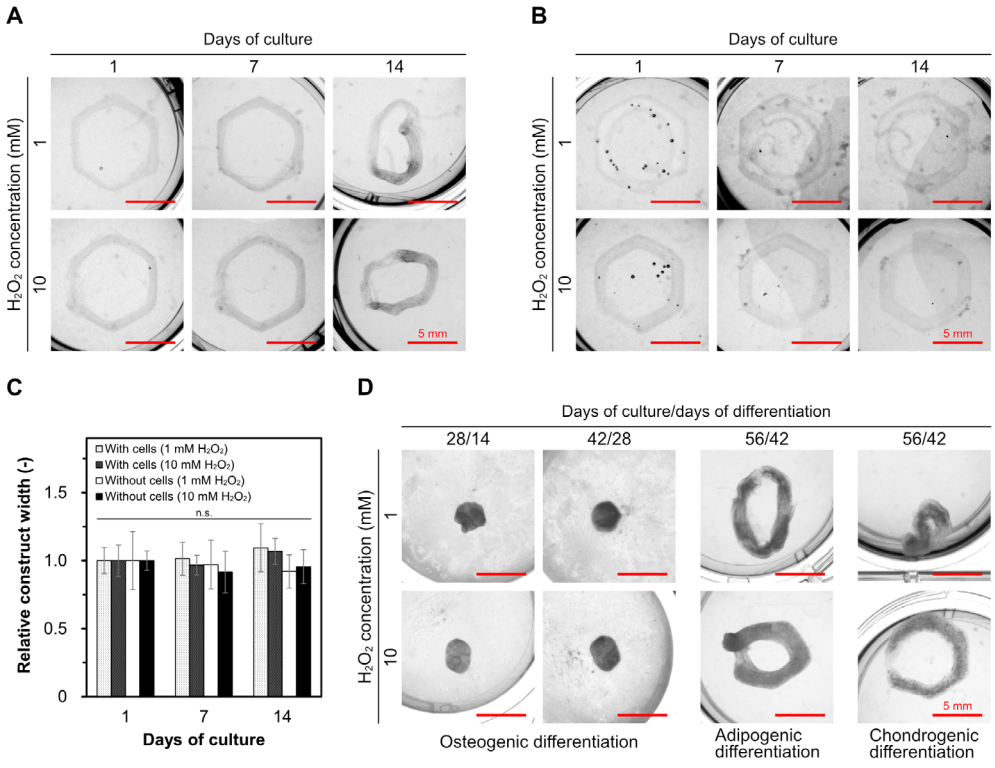


Figure 7. Structural integrity and dimensional changes of biofabricated constructs with and without UE7T-13 cells, and following lineage-specific differentiation. (A, B) Digital images and (C) relative width of constructs comprising 0.5 w/v% hyaluronic acid-phenol, 0.1 w/v% gelatin-phenol, 10 U/mL horseradish peroxidase (HRP) (A) with and (B) without 1×10^6 cells/mL UE7T-13 cells. (D) Digital images of cell-laden constructs after osteogenic, adipogenic, and chondrogenic differentiation induction. The concentrations of HRP in the bioink, carboxyvinyl polymer, and hydrogen peroxide (H_2O_2) in the support material were 10 U/mL, 2.0 w/w%, and 1–10 mM, respectively. The construct width was calculated as the average width of the six sides of each construct and normalized to the width of the same construct on day 1. Notes: Error bars: standard deviation ($n = 6$); n.s.: no significant difference ($p > 0.05$), Tukey's Honest Significant Difference test.

lineage-specific differentiation, this study demonstrates that the CVP/H_2O_2-based support material provides a soft microenvironment suitable for MSC behavior. In addition, altering the H_2O_2 concentration modulated construct properties and MSC differentiation behavior.

Although 3D bioprinting using support materials containing CVP and H_2O_2 has demonstrated potential for MSC applications, several challenges remain. One such challenge, as previously reported, is the difficulty of fabricating thick or structurally homogeneous constructs.[12] This is because the diffusion of crosslinking chemicals becomes limited as the distance from the support material increases, resulting in a decrease in crosslink density within the construct.[12] Consequently, spatial heterogeneity in cellular differentiation may occur within these constructs.[33] Furthermore, the relative contributions of matrix stiffness, porosity, and nutrient and oxygen transport to the observed differentiation behavior remain unclear. We believe this issue can be partially resolved by adjusting the crosslinking density by optimizing the H_2O_2 concentration in the support material and the HA-Ph and gelatin-Ph concentrations in the bioink. Additionally, as described in Section 3.6, soft constructs fabricated using this printing method exhibit significant shrinkage due to cellular contractile forces during lineage-specific differentiation. This shrinkage impedes the diffusion of oxygen, nutrients, and growth factors required for cell survival and differentiation.[54] To address this issue, one possible approach is to incorporate a second ink containing polymer-Ph and HRP, which forms a hydrogel stiffer than the cell-laden regions, into the construct. This is expected to provide structural support that suppresses deformation of the construct. Overall, the potential of this method for applications in tissue engineering is likely to improve through optimizations of printing conditions and compositions of the ink and support material, along with the incorporation of additional functional inks for structural support. This will enable the fabrication of constructs better suited to MSC-based tissue-engineering research while minimizing adverse effects on MSCs.

4. Conclusion

To evaluate the applicability of an extrusion-based 3D bioprinting method for MSCs, in which a support material containing CVP and H_2O_2 was extruded alternately with a bioink, we assessed the MSC-associated properties and differentiation potential of UE7T-13 cells enclosed in printed constructs. During the 14-day culture period prior to differentiation induction, the cells elongated and proliferated within the constructs while maintaining high viability and metabolic activity. Furthermore, these cells retained their mesenchymal phenotype throughout the culture period. Following osteogenic, adipogenic, and chondrogenic induction, the cells successfully produced lineage-specific products, and their amounts were controlled by varying the H_2O_2 concentration in the support materials. Overall, the extrusion-based 3D bioprinting method using a support material containing CVP and H_2O_2 minimized adverse effects on MSC-associated properties and differentiation potential and provided a practical strategy for regulating lineage-specific differentiation, highlighting its potential for stem cell-based 3D bioprinting applications. Future optimization to address these limitations and the integration of multiple bioinks may further broaden the applicability of bioinks that primarily contain polymer-Ph and HRP for tissue engineering and regenerative medicine applications.

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Conflict of interest

Shinji Sakai is an Editorial Board Member of this journal, but was not in any way involved in the editorial and peer-review process conducted for this paper, directly or indirectly. The authors declare they have no competing interests.

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Visualization: Takashi Kotani
Writing–original draft: Takashi Kotani
Writing–review & editing: Takashi Kotani, Shinji Sakai

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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